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Advancement and Contributions of Nanoparticle Technology in Thailand from 2008 to 2024 †

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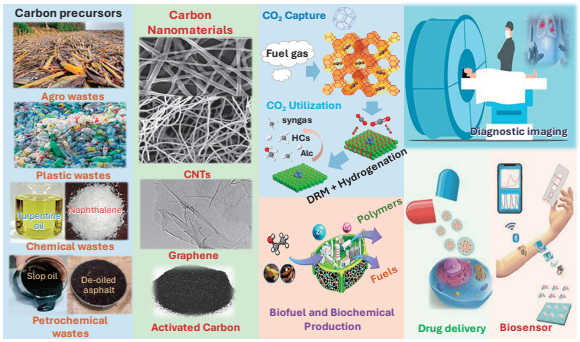
As an extension of Particle Technology (PT), "nanoparticle technology (NPT)" has emerged as a transformative research endeavor in many countries, including Thailand. NPT has delivered significant strides in research, development, and applications. This review paper explores the advancements and contributions of NPT within Thailand's scientific community and industrial sectors by analyzing original technical publications on Thailand's contributions during 2008–2024. Also, a brief mention of the establishment of the Center of Excellence in Particle Technology (CEPT) at Chulalongkorn University and the National Nanotechnology Center (NANOTEC) under the National Science and Technology Development Agency (NSTDA) is given. The key NPT research issues, namely, synthesis methods, characterization techniques, and applications across various disciplines, including medicine, agriculture, and the environment, are selectively reviewed. The paper also discusses collaborative efforts, challenges, and future directions, highlighting Thailand's roles in the global landscape.



Keywords: nanoparticle technology, Thailand, synthesis method, characterization technique, application, collaboration

1. Introduction

In the 1990s, Thailand's industry mainly required conventional Particle Technology (PT), such as dust collection, powder mixing, pneumatic conveying, and comminution. Certain advanced technologies, such as coal-gasification combined-cycle power generation, also drew the attention of industrial players. Fortunately for Thailand, the Society of Powder Technology Japan (SPTJ) and the Association of Powder Process Industry and Engineering (APPIE) decided to help Chulalongkorn University set up a unique Thai Powder Technology Center (TPTC) in 1992 to promote PT as an integrated discipline and serve Thailand's PT community. TPTC subsequently transformed into the Center of Excellence in Particle Technology (CEPT) thanks to the emergent research-promoting policy of Chulalongkorn University.

Gradually, the development of emerging technologies in new material synthesis and characterization, as well as novel applications with a focus on the nanometer scale, has drawn increasing attention from academic and industrial players. In tandem with global industrial advancements, nanomaterials, including NPT, have gained momentum worldwide, and Thailand is no exception. Nanomaterials exhibit unique properties distinct from those of their bulk counterparts, making them invaluable for a wide range of novel applications. Similarly, NPT has revolutionized diverse fields by offering unique properties and functionalities that are achievable only at the nanoscale. Thailand's research and development (R&D) in the NPT has gained momentum over the past two decades, driven by collaborative efforts between academia, government agencies, and industry, particularly since the advent of the National Nanotechnology Center (NANOTEC) under the National Science and Technology Development Agency (NSTDA) in 2003. This review provides an overview of NPT's significance, applications, and Thailand's contributions to the field. Following the approach of Organic and Inorganic Chemistry, nanoparticles (NPs) are classified into two primary categories: carbon-based and non-carbon-based. The former includes carbon nanostructures such as fullerenes, carbon nanotubes, and graphene, which are known for their exceptional strength, electrical conductivity, and versatility. The latter encompasses a broad array of substances such as metal oxides, quantum dots, and nanosilica, each

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with unique properties and applications.

Several reports have summarized the key national characteristics and publication statistics related to nanomaterials for Japan and selected ASEAN countries. Unsurprisingly, Japan is recognized as one of the most technologically advanced countries in Asia, with significant leadership and emphasis on research and development in nanomaterials (Tanthapanichakoon et al., 2014). Here, the authors' collected statistics focus on the annual numbers of international peer-reviewed research publications on NPT as a key metric to gauge research outputs and classify them in terms of the subject areas of NPs. During 2008–2024, Thailand had 4,785 PT and 2,869 NPT publications. **Table 1** shows Thailand's annual research papers on PT and NPT published in peer-reviewed international journals from 2008 to July 2024. As explained in the footnotes of the relevant Tables, the statistics were obtained using ScienceDirect and a suitable combination of search terms. The statistics reveal remarkable growth in NPT research in Thailand, amounting to more than half of conventional PT in the 2020s. This rapid growth in NPT aligns with the global trend thanks to its diverse and effective applications across various fields such as medicine, agriculture, and environmental science. Characterized by their porous structures down to nanoscale dimensions, nanoporous materials are crucial in applications like catalysis, sorption capacity, and gas storage because of their high specific surface area and tunable hierarchical pore sizes.

Table 1 Annual outputs (2008–July 2024) of research articles on conventional particle technology (PT) and nanoparticle technology (NPT) in Thailand.

Year	PT: Research	NPT: Research
2008	164	58
2009	159	60
2010	161	61
2011	224	74
2012	224	106
2013	246	115
2014	232	135
2015	257	140
2016	260	146
2017	281	210
2018	321	198
2019	302	201
2020	327	217
2021	387	283
2022	435	315
2023	427	283
2024	378	268
Total	**4,785**	**2,870**

Although annual numbers are omitted, the total number of NPT research publications coauthored from 2008 to July 2024 by NANOTEC, Mahidol Univ., Kasetsart Univ., King Mongkut's Institute of Technology Ladkrabang (KMITL), and Chulalongkorn Univ. (CU) are 2,059; 291; 262; 145; and 37, respectively. Note that a single publication often has multiple coauthors affiliated with different institutions. This is particularly true for NANOTEC, for which researchers actively and widely collaborate with NANOTEC-funded centers of excellence in external organizations nationwide.

2. Emerging academic activities in NPT in Thailand

Table 2 shows the total number of original PT and NPT research papers from 2008 to July 2024 classified by subject area. It should be noted that the total number of 2,869 research publications since 2008 is significantly fewer than the corresponding sum of the publications in all subject areas because a multidisciplinary publication can belong to more than a single subject area. For NPT, the top four subject areas with decreasing numbers of publications are Materials Science, Chemistry, Chemical Engineering, and Physics & Astronomy. In contrast, the top four subject areas for PT are Materials Science, Engineering, Chemical Engineering, and Chemistry.

In the case of NPT, **Table 2** further classifies the subject areas as focusing on either "NP Synthesis/Production/Manufacture" (a total of 1,113 since 2008) or "NP Applications" (a total of 3,194). For simplicity, it is assumed that an NPT publication that does not focus on the former must belong to the latter, implying that a negligible number of publications focus on both aspects. **Table 2** also classifies the subject areas focusing on "Characterization/Property/Morphology" (a total of 2,659). It is reasonable to assume that all research publications on NP Synthesis must characterize the obtained NPs (a total of 1,113). Therefore, the publications on NP applications that also report on NP characterization have only 2,659 – 1,113 = 1,546 in total, mainly because NP characterization was carried out and reported elsewhere in the corresponding NP synthesis publications.

Due to time and space limitations, the authors decided to focus mainly on NPT subject-area research contributions from 2008 to July 2024 of NANOTEC, Mahidol University (MU), Kasetsart University (KU), KMITL, and CU, respectively, which have corresponding totals of 3,158; 346; 398; 213; and 73; as shown in **Table 3**. There are three major reasons for NANOTEC's prolific NPT contributions. First, NANOTEC researchers belong to 5 well-established multidisciplinary research laboratories and usually work as

Table 2 Classification of types of research articles in each subject area (2008–July 2024).

Subject area	All PT: Research	All NPT: Research	NPT synthesis: Research	All NPT with characterization: Research	NPT applications without synthesis: Research	Applications and/or characterization without synthesis: Research
Materials science	1,707	1,063	332	792	731	460
Chemistry	681	850	178	473	672	295
Chemical engineering	789	495	146	286	349	140
Physics & astronomy	567	444	131	320	313	189
Environmental science	529	247	84	121	163	37
Energy	430	199	68	108	131	40
Biochemistry, genetics & molecular biology	447	303	61	171	242	110
Engineering	789	353	51	178	302	127
Agricultural & biological sciences	659	202	45	123	157	78
Pharmacology, toxicology & pharmaceutical science	224	151	0	87	151	87
Immunology & microbiology	0	0	17	0	–17	–17
Total	**6,822**	**4,307**	**1,113**	**2,659**	**3,194**	**1,546**

Remark
1: Subject areas of multidisciplinary papers are often double- or triple-counted.
Therefore, the tally of all subject areas can significantly exceed the total number of papers shown in **Table 1**.
2: The total numbers of NPT synthesis are obtained by searching all NPT research articles with the search words (synthesis, production, or manufacture) in the titles, abstracts or keywords.
3: The total numbers of NPT characterization are obtained by searching all NPT research articles with the search words (characterization, property, or morphology) in the titles, abstracts, or keywords.
4: The total numbers of NPT applications are obtained by subtracting the number of NPT synthesis from the total number of NPT research articles, assuming that a negligible number of articles reports both the synthesis and application together.
5: The total numbers of NPT applications and/or characterization without synthesis are obtained by subtracting the numbers of synthesis from the corresponding numbers of NPT characterization.

a team on multidisciplinary projects. Second, NANOTEC jointly funded the establishment and operation of 8 centers of excellence (CoE) in 8 top universities nationwide from 2006 to 2011 to promote NPT research and knowledge transfer. From 2013 to 2018, NANOTEC jointly funded 9 CoEs at 8 universities nationwide to promote research projects identified in its National Nanotechnology Road Map. From 2018 to 2022, NANOTEC jointly funded 11 selected labs in 7 universities nationwide, forming the research network of NANOTEC (RNN) to promote NPT applications with an emphasis on collaboration with NANOTEC researchers. Therefore, many coauthored publications by NANOTEC and relevant CoEs were produced. For example, 175 NANOTEC-coauthored publications were produced in the most recent 3-year RNN program. Third, NANOTEC currently boasts nearly 70 researchers and technicians dedicated to NPT research and development projects, numerous advanced research facilities, and significant research budget appropriations from the government and funding from external organizations.

2.1 NP synthesis

Thus far, the bottom-up approach of NP production has been widely adopted for synthesizing various families of NPs and nanocomposites. Thai researchers have employed diverse synthesis methods tailored for specific applications, including chemical, physical, and hybrid methods. This review collected key information on representative techniques, innovative exploration, scalability, and sustainability in NP synthesis and production processes reported by the Thai research community (Charinpanitkul et al., 2008; Kerdnawee et al., 2017; Tanthapanichakoon et al., 2014; Ummartyotin and Manuspiya, 2015).

Several factors contributed to the early growth of NPT research at Chulalongkorn University (CU). The US National Nanotechnology Initiative (NNI), which was launched by former president Bill Clinton, was one of the key stimulants. Meanwhile, the momentum of collaborative

Table 3 Comparison of selected institutions in each subject area (2008–July 2024).

Subject area	All NPT: Research	NANOTEC: Research	Mahidol Univ: Research	Kasetsart Univ: Research	KMITL: Research	Chulalongkorn Univ: Research
Materials science	1,063	847	75	100	90	15
Chemistry	850	570	83	59	34	24
Chemical engineering	495	417	30	60	14	6
physics & astronomy	444	365	16	50	20	1
Environmental science	247	230	23	23	4	3
Energy	199	172	0	17	17	2
Biochemistry, genetics & molecular biology	303	181	45	30	11	11
Engineering	353	192	15	18	12	8
Agricultural & biological sciences	202	100	21	35	10	3
Pharmacology, toxicology & pharmaceutical science	151	84	38	0	0	0
Immunology & microbiology	0	0	0	6	0	0
Computer science	0	0	0	0	1	0
Total	**4,307**	**3,158**	**346**	**398**	**213**	**73**

Remark
A single publication often has multiple coauthors and multiple affiliations. Furthermore, the subject areas of multidisciplinary articles are often double- or triple-counted.
Therefore, the tally of the subject areas for all institutions in Thailand can exceed the total number of articles significantly.

research activities of TPTC, which was established in 1992 in Chulalongkorn University with the strong support of APPIE and SPTJ, provided a seed for NPT research, especially NP synthesis. Major funding agencies, particularly the Thailand Research Fund (TRF), also provided significant driving forces for collaborative research projects, including NPT. Subsequently, the establishment of the National Nanotechnology Center (NANOTEC) in 2003 under the umbrella of the National Science and Technology Development Agency (NSTDA) has played an important role in promoting NPT collaborations among Thai researchers and their alliances from various countries (Tanthapanichakoon et al., 2014; Ummartyotin and Manuspiya, 2015).

To understand the situation of Thailand's competitiveness in nanomaterial research, Tanthapanichakoon et al. (2014) collected and conducted statistical analyses of peer-reviewed research publications and then compared the research performance of ASEAN countries and Japan in terms of publications per million capita. They reported that the productive contributors of NPT research outputs in Thailand included CU, Mahidol Univ., Chiangmai Univ., and NANOTEC. After just one decade, the recent contributions of various research institutions have expanded to a much broader arena. Such research institutions in Thailand have demonstrated a robust commitment to advancing NP synthesis and manufacturing techniques. Various methods such as chemical precipitation, sol–gel synthesis, and green synthesis approaches have been explored to tailor-make NPs with size, shape, and surface properties of interest. Multilateral collaborations among these players are actively involved in various types of NP production, for instance, silver NPs, which have applications in hygiene and environmental applications. These efforts underscore Thailand's capability to innovate and contribute to the global NPs research landscape (Charinpanitkul et al., 2008; Ilcham et al., 2009; Kongsombut et al., 2009; Muangnapoh et al., 2010; Poonjarernsilp et al., 2011; Rattanawongwiboon et al., 2022; Suttiponparnit et al., 2013; Ummartyotin and Manuspiya, 2015; Yamamoto et al., 2012).

In the past, traditional chemical synthesis methods were prevalent, but at present, there is a significant shift toward green synthesis methods focusing on the Bio-Circular-Green (BCG) approach (Chaiwat et al., 2020; Channei et al., 2019; Klanwan et al., 2010; Laochai et al., 2016; Naksuriya et al., 2014; Phongtongpasuk et al., 2017; Sahu et al., 2011; Viriya-empikul et al., 2009). Such eco-friendly methods utilize biological agents like plants, bacteria, and fungi, which are safer and more sustainable compared to conventional methods. In addition, NP research in Thailand has focused on innovative synthesis methods, such as the scalable synthesis of bimetallic NPs using integrated

methods such as impregnation and carbonization. These methods enable high-yield production with controlled particle size, dispersity, and composition, thereby optimizing the catalytic performance. These advancements highlight Thailand's commitment to competitiveness in the field of NP synthesis. This section reviews recent findings and methodologies in NP synthesis, highlighting Thailand's contributions to advancing NP synthesis technologies (Buarod et al., 2015; Inoue et al., 2018; Kerdnawee et al., 2018; Monchayapisut et al., 2019; Vanichvattanadecha et al., 2020).

2.1.1 Selected unique contributions to NP synthesis in Thailand

The number of publications on NP synthesis conducted by Thai researchers has steadily increased, reflecting the promotion of Thailand's contributions to the global NPT field. Synthesis methods encompass a wide range of techniques tailored to produce NPs with specific characteristics. Chemical methods, such as co-precipitation and hydrothermal synthesis, have been extensively studied to produce NPs with precise control over size and composition. Meanwhile, bio-based circular and green synthesis routes utilizing biomass extracts or industrial waste as well as by-products highlight Thailand's commitment to competitive NP production due to the driving force of industrial partners' requirements (Jullakan and Bunkoed, 2021; Kullyakool et al., 2020; Vanichvattanadecha et al., 2020).

As an innovative approach, Viriya-empikul et al. (2009) investigated the effects of reaction time, sonication power, and size of TiO_2 precursor on the characteristics of the resulting titanate nanotubes (TNT), titanate nanowires (TNW), and titanate nanosheets (TNS). Titanate nanostructures were synthesized from anatase and rutile powder of TiO_2 using a hydrothermal method with and without sonication pretreatment at different temperatures (90–180 °C). As a hybrid innovative nanomaterial, WO_3 NPs and multiwalled carbon nanotubes (MWCNTs) constitute a promising nanocomposite. Monchayapisut et al. (2019) explored a facile method to synthesize WO_3 NPs via the nitric acid precipitation route using ammonium tungstate para pentahydrate as a precursor. The precipitation was followed by calcination to incorporate the WO_3 with MWCNTs. The obtained WO_3/MWCNT hybrid nanocomposite was characterized using various techniques, including SEM, XRD, Fourier transform Raman spectroscopy, TGA, and BET analyses, to explore its morphology, crystalline structure, surface functional groups, porosity, and thermal stability. It was found that an increase in the BET surface area of the nanocomposite could be ascribed to the agglomeration of the primary particles by controlled heat treatment to avoid particle sintering.

Phatharachindanuwong et al. (2014) explored the effect of washing–drying methods on the morphology and pores of hierarchical porous silica produced via the sol–gel method. Initially, natural rubber, sodium silicate, and water were mixed at a ratio of 1:2:120. After the suspension was hydrothermally aged at 80 °C for 24 h, the as-obtained precipitate was subjected to three different washing–drying protocols to obtain hierarchical porous silica (HPS). In addition to academic-scale synthesis, Thai researchers have focused on developing scalable manufacturing processes to meet the industrial demands of NPs. Techniques such as microfluidics, spray drying, and electrospinning were investigated to achieve high-throughput production of NPs while maintaining uniformity and quality. These advances are crucial for translating laboratory-scale synthesis methods to practical industrial applications.

As a typical example of the BCG approach, Kerdnawee et al. (2018) explored the possibility of utilizing glycerol, which is a main by-product of biodiesel production, for the synthesis of carbon nanomaterials. As illustrated in **Fig. 1**, the authors employed metallocene, specifically ferrocene ($C_{10}H_{10}Fe$) as a supply of both Fe NP catalyst and carbon atoms for glycerol using a simple set of a syringe pump and a tubular reactor for synthesizing magnetic carbon nanomaterial. They reported an appropriate ratio of glycerol to ferrocene that provided a stable and substantial amount of magnetic carbon NPs. Such a synthesis of magnetic carbon NPs would contribute to both reducing carbon emission (decarbonization) and producing value-added magnetic carbon NPs with possible applications to antibiotic pollutant removal and toxic compound sensing. Subsequently, Chaiwat et al. (2020) explored the utilization of an industrial waste known as slop oil (a mixture of hydrocarbon compounds with a broad spectrum of molecular weights) to synthesize carbon nanomaterials. As depicted in **Fig. 2**, industrial slop oil and its separated fractions could be converted to MWCNTs via co-pyrolysis with ferrocene. Synthesis temperature in the range of 750–950 °C and heating rate in the range of 3–9 °C/min could directly affect the vaporization and decomposition of hydrocarbon precursors to form MWCNTs and derivatives. MWCNTs with nominal diameters of 10–50 nm could be obtained with substantial yields of 45–65 wt% when light hydrocarbons were employed as precursors at a higher growth temperature (850–950 °C) and a higher heating rate of 9 °C/min.

2.1.2 Challenges and prospects

Despite the remarkable progress, challenges such as the reproducibility, scalability, stability, and environmental friendliness of NP synthesis are recognized as one of the ongoing research topics for Thai researchers in the academic and industrial sectors, including the issues of ensuring the safe, effective application, and integration of various NPs on a commercial scale. Prospects include the development of multifunctional NPs and their integration into advanced technological applications such as smart

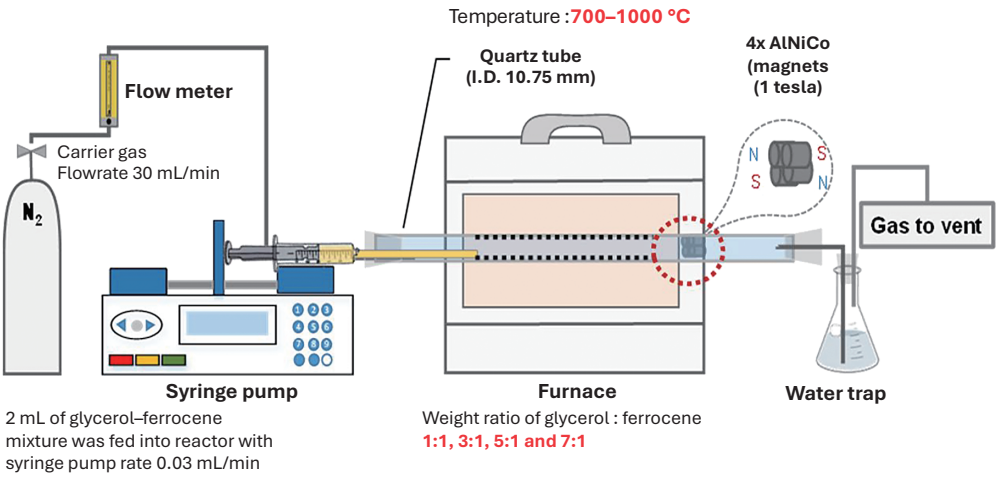

Fig. 1 Schematic of Carbon NP synthesis using co-pyrolysis of glycerol and ferrocene.

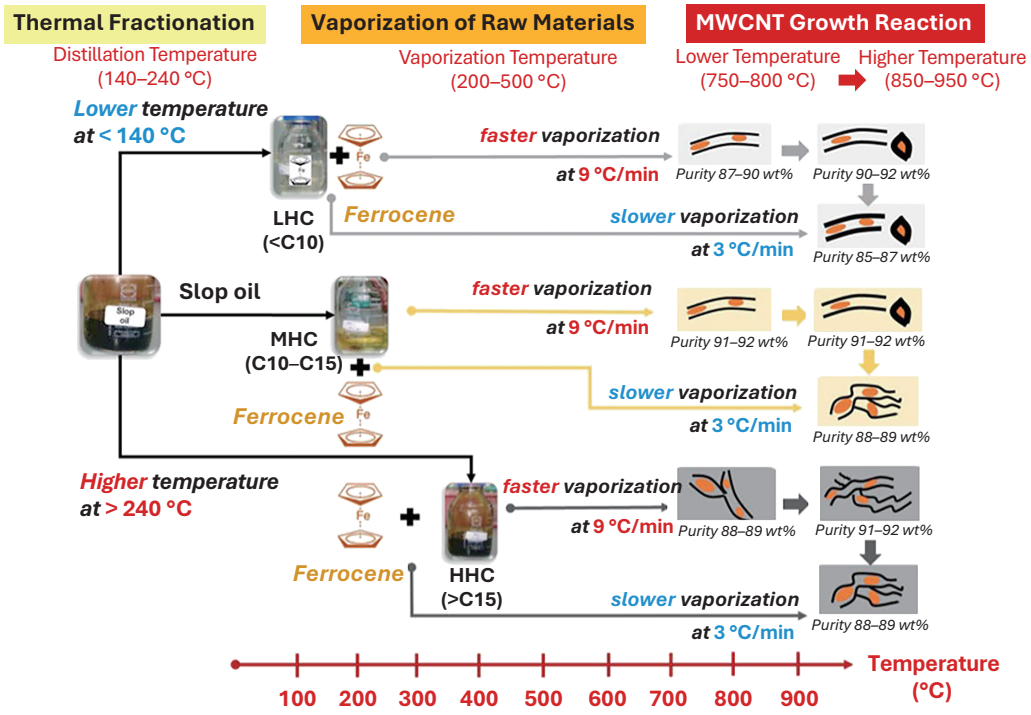

Fig. 2 Synthesis of MWCNTs via co-pyrolysis of hydrocarbon waste and metallocene.

materials. Addressing these challenges requires interdisciplinary collaboration and continued investment in research infrastructure to optimize synthesis protocols and manufacturing workflows. The obtained technical data and know-how of NP synthesis would facilitate extensive research for their applications in various sectors, including drug delivery, environmental remediation, and agriculture, which will be deliberated in **Section 2.3**. In short, Thailand has established itself as a key player in NP synthesis and production, characterized by a robust research ecosystem and technological innovations.

2.2 NP characterization

The entire scope of NP characterization ranges from the determination of fundamental properties of NPs (encompassing particle size distribution, morphology, density, specific surface area, pore size distribution, melting point, surface tension, wettability, crystal structure, and composite structure) to the determination of relevant basic properties depending on the applications of interest (mechanical, thermo-physical, electrical, electrochemical, magnetic, optical, and catalytic properties). Furthermore, when dispersed in a medium such as a liquid, the behavior of NPs is influenced by Brownian movement, aggregation, dispersion, interactions between particles, adsorptive properties, and surface wettability of NPs, as well as slurry rheology.

In short, adequately accurate and essential characterization is crucial for understanding the properties of NPs and

optimizing their applications in fields such as medicine, agriculture, and environmental science. This review covers state-of-the-art characterization techniques employed in Thailand, including spectroscopic methods, microscopy, and surface analysis. The characterization of synthesized NPs is indispensable in research, and numerous NP applications require the proper characterization of the employed NPs.

As shown in **Table 2**, the statistics of Thai NPT research papers addressing the characterization of NPs in each subject area (or application area) were obtained via ScienceDirect using the search words (characterization/property/morphology) in the title, abstract, or keywords. The National Advanced Nano-characterization Center of NANOTEC offers a large variety of testing and characterization services, such as confocal Raman spectroscopy, environmental scanning electron microscopy (E-SEM), focused ion beam (FIB), field-emission scanning electron microscopy (FE-SEM), fluorescence stereomicroscopy (FSM), nano mechanical tester (nano indenter, NMT), and inductively coupled plasma mass spectrometry (ICP-MS) (https://www.nanotec.or.th/en/characterization-and-testing).

One interesting research investigated the synthesis of nickel metals with three different morphologies, namely, nanostar, icosahedra, and microsphere structures, and compared their performance for catalytic carbon dioxide reforming with methane. It was found that nanostar Ni possessed the Ni(111) crystallographic plane with a particle size in the range of 150–200 nm and a BET surface area of 13 m^2/g. Similarly, icosahedra nickel showed a Ni(111) crystallographic plane with larger particle sizes (300–400 nm) and a BET surface area of 20 m^2/g, whereas microsphere nickel exhibited a relatively large cluster size (approximately 3 μm) and BET surface area (114 m^2/g) as a result of the aggregation of Ni(101) nanoplates. The nickel catalysts were tested for their activity in carbon dioxide reforming with methane. Based on the same specific surface area of the catalysts, nanostar Ni showed the highest carbon dioxide and methane conversions due to its crystallographic structure. At 700 °C, the nanostar Ni catalyst exhibited the highest carbon dioxide and methane conversions of 17.6 and 10.5 times those of the microsphere Ni catalyst, respectively (Teabpinyok et al., 2012).

Synchrotron-based X-ray absorption spectroscopy (XAS) is one of the most useful analytical techniques for not only crystalline but also amorphous materials. Unlike X-ray diffraction for selected atoms, this study highlights the use of XAS as a local structural tool in advanced functional materials, including energy storage materials, dielectric materials, and thermoelectric materials (Kidkhunthod, 2017). Information concerning the oxidation states and local atomic structure around probing atoms can be revealed using X-ray absorption near edge structure (XANES) and extended X-ray absorption fine structure (EXAFS). The XAS beamline: BL5.2 at the Synchrotron Light Research Institute (SLRI), Thailand, and its characteristics, including the availability of measured energy ranges, and examples of measured spectra of Mg, S, and Ti K-edge XAS are presented. In addition, the *in situ* XAS setup and experiments conducted at this beamline are outlined.

A good example of the importance of morphology, BET surface area, and metal-support interaction is presented. Titanate nanowire (TNW) and nanotube (TNT) structures were synthesized by the hydrothermal reaction using spherical anatase TiO_2 NP (TNP) as the starting material and then employed as Pd catalyst supports for the liquid-phase selective hydrogenation of 1-heptyne to 1-heptene. Pd dispersion was significantly improved as the specific surface area of the supports increased as follows: Pd/TNT > Pd/TNW >> Pd/TNP. While the hydrogenation rate increased with the number of active Pd^0 sites, the selectivity to 1-heptene was found to depend largely on the degree of interaction between Pd and the support. The catalysts prepared by the impregnation method (I–Pd/TNT, I–Pd/TNW) exhibited stronger metal-support interactions than those prepared by the colloidal route. The selectivity of 1-heptene at complete conversion of 1-heptyne was obtained in the following order: I–Pd/TNT > I–Pd/TNP > Pd/TNT–Pd/TNW > Pd/TNP (Putdee et al., 2013).

Mussel shell waste disposed of by households, restaurants, markets, and farms causes environmental problems worldwide, including in Thailand. Owing to its high calcium (Ca) content from calcium carbonate ($CaCO_3$), some Thai local businesses grind the shell waste into powder and sell it as a bio-source of Ca. Generally, these powdered waste shells are a mixture of various types of mussel shell waste. The researchers investigated and characterized powdered mixed waste shells sold in a local Thai market (so-called mixed shell powder) and ground waste green mussel shells (green mussel shells). The mixed shell powder containing five different types of mussel shells and the green mussel shells were calcined at 800, 900, and 1000 °C for 2 and 3 h, respectively, due to their different particle sizes. They found that an optimal temperature of 1000 °C completely converted $CaCO_3$ to CaO in both samples. Nanoscale particles of CaO have been detected on the surface of calcined shells, making them an interesting bioresource of nano-CaO (Srichanachaichok and Pissuwan, 2023).

Challenges in NP characterization include ensuring reproducibility, dealing with the complexity of NP systems, and addressing potential toxicity and environmental impacts. Overall, Thailand's research community is actively engaged in NPT characterization, thereby contributing to the global advancement of NPT by developing new synthesis methods and novel applications.

2.3 Applications of NPs

NPs have applications across multiple sectors in

Thailand, including biomedicine (drug delivery, imaging), agriculture (crop enhancement, pest control), environment (water purification, pollution control), and advanced materials (electronics, catalysis). Case studies highlight Thailand's advancements and impact in the following selected application areas.

2.3.1 Biomedicine

NPs have emerged as transformative tools for biomedical research and applications. The nanometer scale offers unique advantages such as large specific surface areas, tunable physicochemical properties, and unique optical and electronic characteristics that enable it to cross biological barriers. Moreover, with a comparable scale to biomoieties, NPs can be coupled with various biomolecules for various biomedical applications. In this study, we focused on the advancements made in Thailand regarding the role of NPs in biomedical research. This review explores specific examples of NPs in biomedical applications within the scopes of i) drug delivery and therapeutics, ii) medical imaging, and iii) biosensing systems.

i) Drug delivery and therapeutics

NPs play a significant role in nanomedicine, particularly in drug delivery, with numerous products already on the market and many more in development (Park et al., 2022). Due to their size range comparable to proteins and macromolecules inside living cells, NPs can act as carriers to facilitate the delivery of therapeutic agents. NPs that encapsulate, absorb, or conjugate drugs not only improve drug delivery performance but also protect drugs from the environment, so that their unfavorable biopharmaceutical properties can be masked. Despite their efficacy and safety data, many fully developed drugs struggle to reach clinical use because of their poor solubility and inadequate permeability across the intestinal epithelium, leading to low bioavailability and suboptimal pharmacokinetics. However, when developed correctly, drugs can resist settling and exhibit improved solubility, rapid dissolution, and enhanced adhesion to biological compartments (Vargason et al., 2021). Thus, rapid-onset therapeutic action and improved bioavailability can be achieved. Using nanomaterials for drug delivery can also reduce the necessary drug dosage to achieve therapeutic benefits, thus lowering treatment costs and minimizing side effects associated with specific drugs. As illustrated in **Fig. 3**, various forms of nanocarriers have been employed in drug delivery systems varying from biological substances ranging from proteins, carbohydrates, gelatins, and phospholipids to chemicals such as polymers, carbon materials, and metal NPs (Mitchell et al., 2021). In this review, we focus on three main types of NPs based on research papers published by Thai researchers.

i-1) Liposomes

Liposomes are self-assembled artificial vesicles composed of phospholipids ranging in size from less than 100 nm to several micrometers. They offer attractive biological properties, including biocompatibility, biodegradability, and the ability to entrap both hydrophobic and hydrophilic medications. Liposomes are well-established drug delivery systems in both commercial and clinical settings. However, they also face several challenges, such as low drug encapsulation efficiency, poor stability, and rapid drug release. To address these limitations, many efforts have been made to improve drug stability, extend the circulation half-life for effective drug delivery, and reduce drug toxicity. Over the past two decades, various research groups in Thailand, particularly NANOTEC and the Research Network of NANOTEC (RNN), have made significant contributions to the development of liposomes for encapsulating drugs and genes, establishing them as effective nanocarriers. Wongkhieo et al. (2021) developed

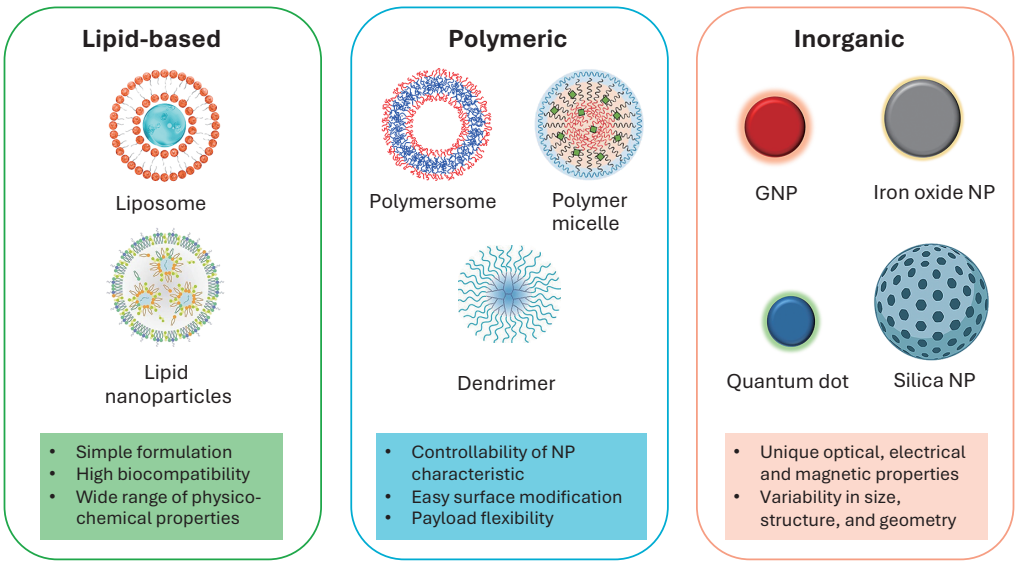

Fig. 3 Class of NPs used in drug delivery.

liposome-encapsulated thiostrepton (TSLP) to target and inhibit breast cancer progression. This liposome formulation significantly enhanced the specificity and cytotoxic activity of thiostrepton, leading to increased cell death in MCF-7 cells in both 2D monolayer and 3D spheroid cultures compared with free thiostrepton. To further improve drug delivery specificity and efficiency, targeting ligands such as antibodies, peptides, or small molecules can be attached to the surface of liposome NPs. Dana et al. (2020) demonstrated a novel approach by combining poly(D,L-lactide-co-glycolide) (PLGA) with liposomes as carriers conjugating with anti-VEGF antibody (Avastin®) for the delivery of cisplatin, a chemotherapeutic drug for cancer treatment. Both in vitro and in vivo studies revealed that the NPs (L-PLGA-Cis-Avastin®) improved specificity for SiHa cells that overexpressed VEGF, resulting in increased cellular internalization and higher accumulation in xenograft tumors (SiHa bearing mice) compared with the free drugs. In addition to drug delivery, liposomes can be incorporated with contrast agents for theranostic purposes. Saesoo et al. (2018) developed a theranostic system consisting of superparamagnetic iron oxide NPs (SPIONs) functionalized with anti-CD20 (Rituximab; RTX). The RTX-conjugated liposome exhibited improved cell internalization, and magnetic resonance imaging (MRI) confirmed the localization of the NPs in the lymphoma xenograft mouse model.

i-2) Polymeric NPs

Polymeric NPs can be fabricated from both synthetic polymers (polylactic acid, polyacrylate, polycaprolactone, etc.) and natural polymers (chitosan, alginate, gelatin, collagen, etc.). Various procedures can be employed to prepare these polymeric particles, including polymerization, solvent evaporation, and emulsification. One of the most attractive advantages of using polymeric NPs as nanocarriers is their stimuli-sensitive properties. By careful design and tailoring, smart polymeric nanocarriers can alter their physicochemical properties in response to environmental signals. For example, physical factors (temperature, light, electromagnetic, ultrasound, and mechanical stress), chemical factors (pH and ionic strength), and biological factors (enzymes, and biomolecules) can serve as stimuli for drug-controlled release. Numerous research groups in Thailand have continuously reported on the design and synthesis of polymeric NPs to improve drug-delivery efficiency and prolong drug-circulation time. For example, Suchaoin et al. (2024) reported the synthesis of doxorubicin (DOX)-loaded melanin NPs as an oral drug delivery system. DOX-loaded melanin NPs exhibit high biocompatibility and a pH-dependent drug release profile, indicating their potential for oral administration, particularly in cancer treatment. Meanwhile, Chittasupho et al. (2014) demonstrated the use of the peptide LFC131 conjugated with PLGA NPs loaded with DOX. The LFC131–DOX NPs showed rapid and high cellular uptake by target A549 lung cancer cells with sustained release of DOX, indicating their potential as a controlled-release drug delivery system. In addition, Pornpitchanarong et al. (2020) reported on polymeric N-vinylpyrrolidone (NVP) NPs conjugated with cisplatin for the treatment of oral cancer. The NPs demonstrated strong anticancer effects against HN22 oral cancer cells, showing higher cellular deposition of cisplatin in the earlier period. This finding suggests a slower but safer cancer-killing effect.

i-3) Inorganic NPs

Gold NPs (GNPs) are one of the most promising metal scaffolds for drug delivery because of their ease of synthesis, low toxicity, well-established surface functionalization, and tunable stability. Therapeutic agents attached to GNPs can be efficiently released through internal stimuli (pH or glutathione) or external stimuli (light or electromagnetic field). Moreover, hyperthermia treatment and photodynamic therapy can be integrated into these drug delivery systems to enhance tumor destruction. Thai research groups have consistently advanced the development of drug delivery systems based on GNPs. For instance, Laksee et al. (2020) demonstrated the green fabrication of a hybrid drug carrier system using a targeting pullulan derivative combined with GNPs. The anticancer drug DOX was then loaded onto the hybrid drug carrier, which exhibited pH-responsive release of DOX from the formulation. In addition to drug delivery, GNPs have also been used as carriers to deliver genes, peptides, and other biomolecules for specific purposes. Sansanaphongpricha et al. (2020) introduced a new platform to enhance the efficiency of peptide delivery to chondrocytes and human mesenchymal stem cells (hMSCs) for cartilage regeneration using BMP2 peptide-conjugated gold nanorods (GNRs). BMP2–GNRs significantly promoted cellular uptake of the peptides in both hMSCs and porcine chondrocytes, resulting in notable activation of type II collagen gene expression, as evidenced by confocal microscopy.

ii) Medical imaging

Medical imaging technology plays a vital role in early diagnosis and effective monitoring of therapeutic responses in various diseases, particularly cancer. Imaging modalities such as magnetic resonance imaging (MRI), X-ray radiography, computed tomography (CT), ultrasound (US), positron emission tomography (PET), single photon emission computed tomography (SPECT), and fluorescence imaging have been utilized in clinical settings to obtain accurate anatomic and functional information. NPs have been used as contrast agents to enhance the distinction between normal tissues and abnormal lesions, thereby contributing to higher accuracy and precision. Owing to their nanoscale size, these particles facilitate improved biodistribution, prolonged half-life in blood circulation, enhanced cellular uptake, and effective tumor penetration and

localization. In this review, we summarize the applications of NP-based contrast agents across various imaging modalities, with a particular focus on fluorescence and MRI techniques, which are the two most prominent areas of medical imaging research in Thailand.

ii-1) Fluorescence imaging

Fluorescence technology is one of the most widely used techniques in biomedical imaging due to its high spatial resolution at the microscopic level, especially within the near-infrared (NIR) region, which ranges from 650 to 1700 nm. However, it faces several challenges, including limited penetration depth, autofluorescence, and scattering in tissues, which continue to hinder clinical utility (Li et al., 2020). Additionally, most commercial organic dyes applied for cancer cell tracking and analyzing genes, including proteins, suffer from limited stability and susceptibility to photobleaching. To address these limitations, NP-based fluorescence agents have been developed and synthesized with surface modification to facilitate both active and passive targeting (Cai et al., 2011). For example, Treerattrakoon et al. (2017) demonstrated the fabrication of silica NPs doped with Cy5 dye (Cy5–SiNPs) conjugated with antibodies targeting the biomarker epithelial cell adhesion molecule (EpCAM). These synthesized NPs were used for the in vitro detection of HT-29 colon cancer cells and for in vivo fluorescence imaging in mice with HT-29 tumors. Another example involves core–shell fluorescent NPs, in which aggregation-induced emission (AIE) dyes are embedded in a biocompatible polymer (Hiranmartsuwan et al., 2022). New AIE compounds were synthesized to achieve a strong fluorescence signal for cellular imaging of H1299 lung carcinoma cells. These NPs were also applied for in vivo and ex vivo imaging of a bladder cancer murine model, indicating that the take-up was localized at the tumor site.

ii-2) Magnetic resonance imaging (MRI)

MRI is a powerful imaging technique that offers high spatial resolution, excellent intrinsic soft-tissue contrast, and 3D anatomical tomographic information, making it a mainstay in clinical practice. However, the limitations of MRI are high costs, long imaging times, and artifacts from patient motion and implant presence. To address these challenges, MRI contrast agents, particularly superparamagnetic iron oxide NPs (SPIONs) with surface modifications and core–shell structures, have been developed to enhance differentiation between lesions and healthy tissues. For instance, SPIONs encapsulated within chitosan-triphosphate NPs (SPIONPs–CS) were prepared and applied to T1- and T2-weighted images (Sanjai et al., 2014). The resulting SPIONP–CS exhibited improved MRI contrast with low cytotoxicity and excellent stability over extended periods. Recently, a novel approach combining MRI and SPECT imaging modalities was reported for liver cancer diagnosis. Such an NP system, consisting of SPIONs and Technetium-99m as contrast agents in micelles, provided high signal intensity in both SPECT and MRI for hepatocellular carcinoma cells, indicating the successful fabrication of NP-based contrast agents for dual imaging modalities.

iii) Biosensing system

Biosensors are analytical tools designed to monitor and respond to changes in biological processes. They recognize specific targets and convert these interactions into measurable signals through transducer elements (**Fig. 4**). In medical applications, biosensors have been specifically developed to detect a range of biomarkers associated with diseases, including DNA, RNA, proteins, metabolites, cells, bacteria, and viruses, in biological samples for diagnosis and disease staging. As mentioned earlier, NPs possess distinctive properties at the nanoscale, which are influenced by their size, shape, composition, and surface characteristics. Considering these findings, NPs can be integrated into biosensing systems for signal transduction, sample preparation, and enhanced detection signals, with the goal being increased sensitivity and accuracy in target analyses. This section provides an overview of the major biosensor platforms extensively researched in Thailand, including: 1) colorimetric 2) fluorescence 3) surface-enhanced Raman scattering (SERS), and 4) electrochemical biosensors.

iii-1) Colorimetric biosensors

Colorimetric detection is one of the simplest and most cost-effective NP-based biosensing methods. The proposed approach relies on a shift in the peak position of localized surface plasmon resonance (LSPR) of NPs as the transduction signal for analyte detection. A common type of colorimetric sensor is aggregation-based detection using GNPs functionalized with a biorecognition element that captures the target analyte. When the target binds to the biorecognition element, it changes the dielectric environment surrounding the GNPs, leading to a shift in the LSPR peak and a corresponding color change. Typically, single-stranded DNA (ssDNA) or antibodies can be attached to GNPs as targeting ligands to capture various targets, including DNA, proteins, cells, bacteria, drugs, and small molecules, by inducing color changes associated with aggregation-based detection. A notable application of NP-based colorimetric detection is the lateral flow immunoassay (LFA), which is commonly used for home pregnancy tests and COVID-19 antigen test kits. To illustrate the working principle of the LFA, a schematic representation of a typical LFA structure is provided in **Supplementary Fig. S1(a)**. In a collaborative effort involving NANOTEC, BIOTEC, and Ramathibodi Hospital, Wiriyachaiporn et al. (2024) reported the development and preclinical testing of the LFA platform for detecting the SARs-CoV-2 nucleocapsid protein for COVID-19 screening during the recent pandemic (**Supplementary Fig. S1(b)**). Under optimum conditions,

Fig. 4 Primary components of biosensors for biomarkers detection.

the system enabled direct visual detection of the nucleocapsid protein, achieving a detection limit in the nanogram range of nucleocapsid protein within 15 minutes with 98 % sensitivity and 100 % specificity compared with the standard molecular method (RT-PCR).

iii-2) Fluorescence biosensors

The fluorescence approach has become widely used in biosensing due to its high sensitivity, simplicity of operation, and viability. Commonly, organic dyes are attached to biorecognition elements to generate fluorescence signals indicating biomolecular reactions. However, conventional fluorophores often suffer from instability and photobleaching, which limit their detection sensitivity. While Quantum dots (QDs) provide brighter fluorescence, their surfaces require modification to enhance their aqueous solubility and reduce their toxicity. In this context, fluorescence-doped silica NPs (FD-SiNPs) have emerged as promising candidates for highly sensitive and photostable probes in bioanalysis. A large number of dye molecules inside each SiNP resulted in excellent photostability and increased the dye-to-biomolecule labeling ratio, leading to high signal detection. Previously, Bamrungsap et al. (2014) in collaboration with NANOTEC and Siriraj Hospital, demonstrated the preparation of Cy5-doped SiNPs as signaling probes for fluorescence-based LFA for the detection of influenza A using a portable strip reader. Under optimized conditions, the developed fluorescence-based LFA could detect a recombinant nucleoprotein, a biomarker of influenza A, with 8 times better sensitivity than that of a commercial colorimetric LFA for influenza A screening.

iii-3) SERS biosensors

Raman scattering can be used to identify molecules by analyzing their unique vibrational fingerprints. However, the typically low cross-section of Raman scattering yields insufficient signals for high-sensitivity detection in biosensing applications. Metallic NPs, particularly silver NPs (AgNPs) and GNPs, can significantly increase sensitivity through surface-enhanced Raman scattering (SERS) when a Raman molecule is attached to the surface. Consequently, SERS biosensors have become important tools for biomarker detection in recent years due to their high sensitivity at the single-molecule level. In SERS-based biosensors, the target is labeled with a ‘SERS tag’ consisting of four counterparts: metal NPs, Raman molecules, coating layers and biorecognition elements, as illustrated in **Supplementary Fig. S2**. The fabrication of SERS tags using GNRs conjugated with an aptamer specific to cervical cancer cells was previously reported (Bamrungsap et al., 2016). These SERS tags demonstrated specificity to Hela (cervical cancer) cells through aptamer-protein interaction, resulting in strong SERS signals. A similar SERS tag design was used for the detection of miR-29a, a biomarker associated with several cancers, by combining it with DNA-conjugated magnetic NPs (MNPs) as a capture probe (Treerattrakoon et al., 2022). This system has high sensitivity, a limit of detection (LOD) of 10 picomolar (pM), and good selectivity for serum assays. With advancements in machine learning (ML) technology, ML analysis has been performed on improving SERS-based diagnostic performance. Recently, SERS chips were fabricated and integrated with ML analysis to screen latent tuberculosis infection (LTBI), achieving high accuracy up to 95 % (Eiamchai et al., 2024).

iii-4) Electrochemical (EC) biosensors

Electrochemical (EC) sensors have drawn extensive attention from researchers over the past decades because of their advantages in cost-effectiveness, portability, ease of operation, rapid response, high sensitivity, and simple construction. In EC biosensors, changes in the electrical signals caused by EC reactions of target components on the electrode surface are monitored and recorded. To boost the

detection sensitivity, conductive NPs, such as metal NPs, MNPs, and carbon-based NPs, are applied to modify the electrode surface. Due to their special physicochemical properties, large surface area, excellent electron-transfer ability, and strong interaction with biological molecules, effective NP modification can lead to high-performance EC biosensors. Several research groups in Thailand are actively developing high-performance EC biosensors for biomarker detection using different strategies and various types of nanomaterials. For instance, Yaiwong et al. (2021) developed an EC biosensor for matrix metalloproteinase-7 (MMP-7) cancer biomarkers using a screen-printed carbon electrode (SPCE) modified with a two-dimensional molybdenum disulfide (2D-MoS_2)/graphene oxide (GO) nanocomposite, followed by anti-MMP-7 capture antibodies. This EC biosensor exhibits very high picogram detection sensitivity with high selectivity and reproducibility. The EC biosensor can be integrated with other detection platforms to enhance its accuracy and efficiency. For example, a dual-mode EC/SERS biosensor was recently demonstrated for prostate cancer detection (Yaiwong et al., 2024). This dual-mode immunosensor provided strong SERS and EC responses, effectively quantifying PSA protein in human serum samples at the picogram range, with good recovery.

Over the last decade, research on NPs in Thailand's biomedical fields has experienced substantial growth and diversification. Researchers have increasingly focused on developing various types of NPs for drug delivery, cancer therapy, imaging, and biosensing applications. The target drug delivery system development aims to design NPs that specifically deliver drugs to cancer cells, minimizing side effects while improving treatment efficiency. The integration of imaging diagnosis and therapy, known as theranostic, has gained increasing attention recently. Additionally, novel NPs have been synthesized and used for developing highly sensitive biosensors for detecting biomarkers associated with various diseases. With advancements in NP design and synthesis, these approaches enable early diagnosis and treatment of diseases, resulting in better patient outcomes.

2.3.2 CO_2 capture and utilization (CCU)

Over recent decades, CO_2 emissions in Thailand have gradually increased due to economic growth, industrialization, and urbanization. Carbon capture and utilization (CCU) has attracted growing interest because it addresses climate change and offers potential benefits by reducing dependence on conventional fossil fuels. NPs have played and will continue to play an important role as adsorbents and catalysts in this field. As illustrated in **Fig. 5**, CO_2 can be directly captured from industrial processes or flue gases in power plants and then utilized without H_2 in some applications, such as mineralization and carbonization, to produce carbonate products. However, when targeting hydrocarbon fuels and chemicals, hydrogen is essential for CO_2 catalytic conversion. Additionally, it is critical that the energy required for the CCU processes comes from renewable sources to ensure a neutral or negative carbon footprint during the entire operation.

Current research in Thailand has focused on the development of low-cost, high-potential adsorbents and catalysts. A statistical analysis of CCU over the last 16 years (2008–2024) was conducted using Scopus and bibliometric analysis software. The annual publication rate of research on CO_2 adsorption in Thailand has shown a consistently rising trend, with a sharp rise in 2024 (**Fig. 6(a)**). In contrast, trends in CO_2 hydrogenation and dry reforming of methane (**Fig. 6(b)** and **6(c)**) peaked in 2021 and 2022, respectively. The significant growth in research between 2020 and 2022 can be attributed to the rising CO_2 emission, leading to increased interest in CO_2 reduction technologies. However, the decline in publication rates following this period may be linked to the impact of the COVID-19 pandemic. This section focuses on recent advancements in the application of NPs in CCU research in Thailand, particularly in the areas of i) CO_2 capture and ii) CO_2 use via thermal catalytic processes.

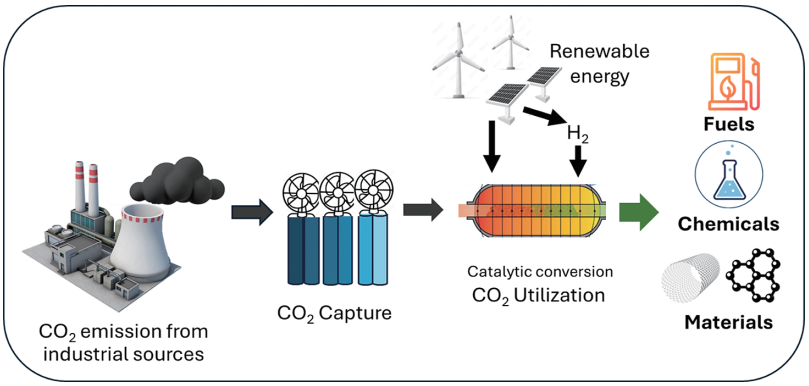

Fig. 5 Overview of carbon capture and utilization technologies (CCU).

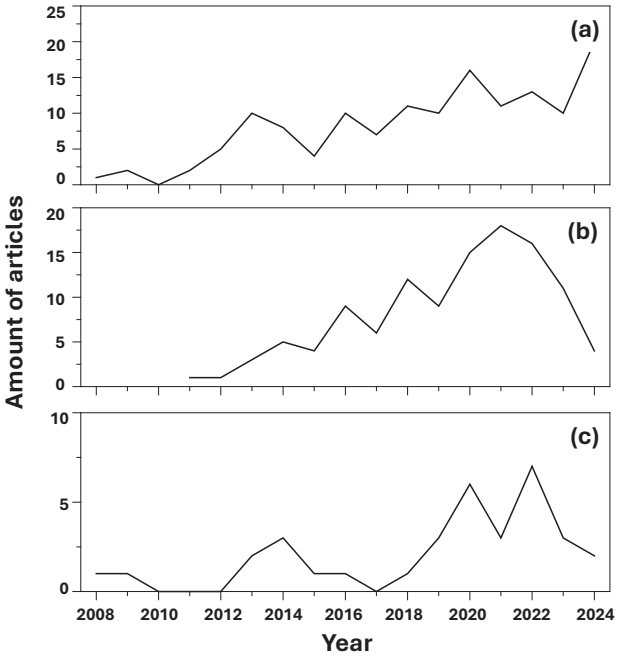

Fig. 6 Thailand's research publication trends from 2008 to 2024 in **(a)** CO_2 adsorption, **(b)** CO_2 hydrogenation, **(c)** dry reforming of methane.

i) CO_2 capture

CO_2 capture, particularly via adsorption, has been increasingly recognized as one of potential technologies for reducing industrial CO_2 emissions and addressing global climate change. Various CO_2 capture technologies have been developed and demonstrated. While amine-based solvents for large-scale CO_2 scrubbing are well-established, they are associated with high operational costs and stability issues, posing significant research challenges. Currently, solid adsorbents offer a promising alternative due to their high selectivity and capacity, lower energy requirements, ease of regeneration, resistance to degradation, and overall cost-effectiveness with a lower environmental impact (Nimmanterdwong et al., 2017). Thailand's research has focused on the mechanisms of CO_2 capture, types of solid adsorbents, and process design and development. Various solid adsorbents, including zeolites (Boonchuay and Worathanakul, 2022; Punpee et al., 2023; Sangsuradet et al., 2022; Sangsuradet and Worathanakul, 2024), metal-organic frameworks (MOFs) (Chanajaree et al., 2019; Puphasuk and Remsungnen, 2016; Teerachawanwong et al., 2023), alkaline oxides/carbonates (Chandarin et al., 2023; Muchan et al., 2020; Thunyaratchatanon et al., 2017), and carbon materials (Borisut et al., 2024; Rattanaphan et al., 2020; Sitthikhankaew et al., 2014; Tangsathitkulchai et al., 2021), have been studied for CO_2 capture.

As an overview, researchers identified zeolites as the best materials for CO_2 adsorption due to their highly ordered pore structure, high surface area, and outstanding chemical and thermal stability. Kongnoo et al. (2017) synthesized zeolite 13X from palm-oil-mill fly ash and found that its CO_2 adsorption capacity was 6.42 mmol/g at 4 bar and 32 °C, which was 22 % higher than that of the nonactivated zeolite 13X and 11 % higher than that of the commercial zeolite 13X. Boonchuay and Worathanakul (2022) investigated the behavior of zeolite 5A and the conditions for CO_2 adsorption using a CO_2/N_2 gas mixture in a fixed-bed column. The highest CO_2 adsorption capacity of 7.42 mmol/g was achieved at a CO_2 concentration of 80 %vol in the gas mixture and a gas flow rate of 1 l/h at 25 °C. CO_2 adsorption by zeolite 5A indicated that physical adsorption with intraparticle diffusion was the rate-limiting step of the overall process. Parinyakit and Worathanakul (2021) found that the highest CO_2 adsorption capacity of Zeolite 4A (5.86 mmol/g) was achieved at 0 °C and 10 bar.

Other high-potential materials used for CO_2 capture include MOFs, alkaline oxide/carbonate sorbents, and activated carbons (AC), each offering distinct advantages. MOFs such as ZIF-8 and MIL-88A are highly regarded for their high surface area, tunable porosity, and diverse structures, which render them efficient for CO_2 adsorption (Chokbunpiam et al., 2016; Puphasuk and Remsungnen, 2016). Their CO_2 adsorption capacities at 25 °C and 1 bar ranged from 0.94 to 5.78 mmol/g. Alkaline oxide/carbonate sorbents stand out for their simplicity, cost-effectiveness, ease of regeneration, and wide availability, making them promising for large-scale applications. Bio-based CaO and K_2CO_3/Al_2O_3 sorbents have exhibited high CO_2 sorption capacities of 4.34 to 7.05 mmol/g (Boonprasop et al., 2018; Charoenchaipet et al., 2020; Jaiboon et al., 2013; Jamrunroj et al., 2019; Phanthasri et al., 2024). Additionally, biomass-derived activated carbons are favored for their low cost, high surface area, moisture resistance, and strong CO_2 adsorption capacity at ambient pressure, making them viable for carbon capture. To enhance their adsorption properties, ACs were modified with organic chemicals such as diethanolamine (DEA), ethylenediamine, and polyethyleneimine (PEI), resulting in improved CO_2 capture capacities ranging from 3.59 to 5.30 mmol/g, depending on the adsorption temperature and pressure (Kongnoo et al., 2016; Rattanaphan et al., 2020; Sirinwaranon et al., 2023; Thubsuang et al., 2023). Further research details on other materials for CO_2 adsorption are provided in **Supplementary S3**. Continued research and development in CO_2 adsorbent materials, process design, and cost reduction are essential for overcoming the current limitations and advancing these technologies for large-scale applications.

ii) CO_2 use

Recent CO_2 use via thermal catalytic processes, namely hydrogenation, methanation, and dry reforming, has been accepted as a sustainable technology for converting waste CO_2 to synthetic fuels and value-added chemicals.

ii-1) CO_2 hydrogenation reaction

The use of CO_2 via the hydrogenation process not only mitigates the global warming problems but also provides value-added feedstocks and alternative fuels for the chemical industry. The CO_2 hydrogenation to useful products (e.g., CH_4, CH_3OH, and their derivatives) includes the reactions shown in **Eqns. (1)–(4)** (Kiatphuengporn et al., 2017; Numpilai et al., 2021; Ratchahat et al., 2021; Witoon et al., 2022a, 2022b).

The methanol formation

$$CO_2 + 3H_2 \leftrightarrow CH_3OH + H_2O \quad \Delta H_{298K} = -49.5 \text{ kJ/mol} \tag{1}$$

The methanation reaction

$$CO_2 + 4H_2 \leftrightarrow CH_4 + 2H_2O \quad \Delta H_{298K} = -165.0 \text{ kJ/mol} \tag{2}$$

The reverse water–gas shift (RWGS) reaction

$$CO_2 + H_2 \leftrightarrow CO + H_2O \quad \Delta H_{298K} = 41.2 \text{ kJ/mol} \tag{3}$$

Fischer–Tropsch synthesis (FTS) for light olefin production

$$nCO + 2nH_2 \leftrightarrow (-CH_2-)_n + nH_2O \tag{4}$$

Due to the chemical inertness of CO_2, the reaction typically requires elevated temperatures (200–300 °C) or/and high pressures (50–100 bar) to facilitate the CO_2 activation. CO_2 hydrogenation to methanol is particularly important, as methanol serves as a platform molecule and an alternative fuel. Many studies have explored key factors for sustainable development in CO_2 hydrogenation and alcohol selectivity, including reactor types, metal catalysts, supports, promoters, catalyst preparation methods, and operating conditions (Kiatphuengporn et al., 2014; Phongamwong et al., 2017; Satthawong et al., 2014; Thilakarajan, 2024; Witoon et al., 2016a). Extensive research has shown that Cu-based catalysts are effective for methanol production via CO_2 hydrogenation, while Fe, Co, and Ni-based catalysts are commonly used for methane production. Various oxide additives and supporting materials, such as ZnO, Al_2O_3, ZrO_2, Ga_2O_3, Y_2O_3, TiO_2, and SiO_2, have been employed in these catalysts.

The Cu–Zn (CZ) catalyst was found to be effective for methanol production. When modified with chitosan as a precipitating agent, CZ resulted in smaller CuO crystallite sizes on hollow CuO–ZnO nanospheres, which promoted a higher space–time yield (STY) of methanol compared to the unmodified catalyst. At 240 °C with time on stream of 30–40 h, the catalyst achieved a high CO_2 conversion of 14.8 % with CH_3OH selectivity of 54 % and an impressive CH_3OH STY of 135 mg/g_{cat}·h (Witoon et al., 2013). Deerattrakul et al. (2016) used reduced graphene oxide (rGO) as a support for CZ and found that it significantly enhanced the catalytic activity and improved the dispersion of CZ particles. The 10 wt.% CuZn/rGO catalyst achieved the highest CH_3OH STY of 424 mg/g_{cat}·h at 250 °C and 15 bar. Additionally, a catalyst with 15 % CuZn loaded on nitrogen-doped graphene aerogel, using urea as a precursor, provided the highest CH_3OH STY (405.49 mg/g_{cat}·h) due to the highest pyridinic-N content. Witoon et al. (2016b) found that CH_3OH yield was enhanced by the strong interaction between the Cu metal and the support, along with an increase in the Cu surface area. The Cu site-specific activity of Cu loaded on *t*-ZrO_2 (*t*-: tetragonal) was 1.10–1.50 and 1.62–3.59 times higher than those of Cu/*a*-ZrO_2 (*a*-: amorphous) and Cu/*m*-ZrO_2 (*m*-: monoclinic), respectively. Witoon et al. (2016b) also demonstrated that the addition of Zn to a binary CuO–ZrO_2 catalyst improved Cu dispersion and increased the number of active sites for CO_2 and H_2 adsorption. The optimum Cu–Zn–Zr (CZZ) catalyst composition of 38.2:28.6:33.2 resulted in a superior CO_2 conversion and CH_3OH productivity of 219.7 mg/g_{cat}·h at 240 °C. Furthermore, the influence of GO on the CZZ was investigated. 1 wt.% GO-supported CuO–ZnO–ZrO_2 (CZZ–1GO) exhibited the highest CH_3OH selectivity of 75.9 % at 200 °C and 20 bar. The GO nanosheets served as a bridge between mixed metal oxides, promoting hydrogen spillover from the Cu surface to the carbon species adsorbed on the isolated metal oxide particles, resulting in a remarkable enhancement of CH_3OH production.

Kiatphuengporn et al. (2014) studied the effect of the pore characteristics of supports for bimetallic Fe–Cu catalysts. 3 wt.% Fe–10Cu on bimodal MCM-41 exhibited the highest CO_2 conversion of 20.8 % at 350 °C and the highest alcohol selectivity of 80–99 % at lower reaction temperatures (160–200 °C). The presence of larger mesopores on the bimodal MCM-41 significantly enhanced the catalytic performance by promoting the formation of larger metallic particles, resulting in less metal-support interactions, which were more favorable for this reaction. Furthermore, an external magnetic field was applied to improve the catalytic performance (Kiatphuengporn et al., 2016, 2017; Munpollasri et al., 2022). Over Cu–Fe/MCM-41 catalysts with intrinsic magnetic properties, CO_2 conversions with a magnetic flux density of –27.7 mT in the north-to-south (N–S) direction were significantly improved by 1.5–1.8 times; meanwhile, the activation energy decreased by 1.12–1.15 times compared to those without a magnetic field. Higher selectivity to C_2–C_3 hydrocarbons (2.5–5.3 times) and CH_3OH (1.6 times) were observed. Umchoo et al. (2018) also focused on the application of magnetic fields and investigated the effects of supports, including infiltrated core–shell mesoporous silica–aluminosilicate materials. The highest CO_2 conversion was achieved using the Fe–Cu/infiltrate catalyst under a magnetic field at 260 °C, which was 1.5 times higher than that obtained without a magnetic field. At 240 °C, the CH_3OH and dimethyl ether (DME) STY were 1.8–1.9 times higher than those without a magnetic field. These remarkable catalytic performances can be attributed to the magnetic field enhancing CO_2

adsorption on the magnetized catalyst surfaces, which led to increased activity, reduced apparent activation energy, and improved product selectivity in the heterogeneous catalysis process. An additional research overview of CO_2 hydrogenation to other products, including DME, light olefins, and methane, is provided in **Supplementary S3**.

ii-2) Dry reforming of methane (DRM)

Dry reforming of methane (DRM) has been promoted as a promising technology for converting two important greenhouse gases, carbon dioxide (CO_2) and methane (CH_4), to syngas (H_2 and CO), as shown in **Eqn. (5)**. Syngas can be used as feedstock to produce hydrocarbons as fuels or chemicals through Fischer–Tropsch synthesis (Witoon et al., 2011).

$$CO_{2(g)} + CH_{4(g)} \leftrightarrow 2CO_{(g)} + 2H_{2(g)} \quad \Delta H = +247\ \text{kJ/mol} \tag{5}$$

The DRM process typically requires high temperatures (700–900 °C) to promote CO_2 and CH_4 conversion and the synthesis of gas yield, which, in turn, encounters several issues in the DRM system (Aieamsam-Aung et al., 2022; Kuboon et al., 2022; Saconsint et al., 2023). The two major drawbacks of high-temperature DRM are coke formation and metal sintering. The former inevitably occurs in a highly endothermic reaction during the CH_4 decomposition and CO disproportionation steps within the DRM pathways, eventually hindering the metal active sites. The latter is caused by a thermal effect that induces the merging of tiny metal particles into larger ones with fewer active sites. DRM studies in Thailand aim to prevent these side effects and explore mitigating approaches (Tungkamani et al., 2013). Another application of this process is the production of high-quality carbon nanotubes (CNTs) (Rattanaamonkulchai et al., 2022a, 2022b; Saconsint et al., 2023; Sae-tang et al., 2024) (for more details, see **Supplementary S4**). The influences of the metal catalyst structure, catalyst support, promoter, and reaction conditions on the performance have been investigated (Teabpinyok et al., 2012).

Among metal catalysts, low-cost Ni-based catalysts have received attention owing to their high activity in CO_2 reforming with CH_4 (Chuenjai et al., 2022; Phongaksorn et al., 2015; Therdthianwong et al., 2008). However, compared with noble metals, the deactivation rate of Ni catalysts is relatively high due to carbon deposition on their active sites. Recent studies have reported that Ni-based catalysts supported over various materials, such as SBA-15, CeO_2, MgO, *h*-BN, and Al_2O_3, are effective for the DRM reaction (Chaisamphao et al., 2021; Chotirach et al., 2020; Kuboon et al., 2022; Ratchahat et al., 2021; Saconsint et al., 2023). The active surface area of Ni-based catalysts can significantly affect the decomposition of CH_4 or CH_x species. Teabpinyok et al. (2012) demonstrated that Ni morphologies, including nanostars, icosahedra, and microspheres, influence the catalytic activity and deactivation due to carbon deposition. At 700 °C, nanostar Ni exhibited the highest CO_2 and CH_4 conversion rates, 17.6 and 10.5 times higher than those of icosahedra and microsphere Ni catalysts, respectively, due to its unique crystallographic structure. Donphai et al. (2014) applied CNTs in conjunction with Ni metal clusters to mesocellular silica (MS). The Ni–CNTs/MS catalysts significantly improved the catalyst stability in DRM at 650 °C for 24 h while simultaneously inhibiting the reverse water–gas shift reaction compared to Ni/MS catalysts. This outstanding activity can be attributed to the selective formation of carbon by-products during the tube-length extension of existing CNTs, which helped maintain the active surface of the Ni–CNTs/MS catalysts. Phichairatanaphong and Donphai (2023) also developed a modified support with enhanced basicity. A Ni catalyst supported on a cerium–zirconium composite (CeZr) exhibited a high CO_2 conversion of 70 % over a 10-h time on stream (TOS) at 700 °C, attributed to improved Ni dispersion, thermal stability, surface basicity, and oxygen vacancies in the CeZr structure, which led to a reduced degree of coke formation and metal sintering. In another study, Phichairatanaphong et al. (2023) incorporated a quadruple oxide support based on similar concepts as their previous work, focusing on oxygen vacancies and surface basicity. By adding NiO–MgO solid solution and $MgAl_2O_4$–$ZnAl_2O_4$ spinel to the complex, the catalytic activity reached 80 % CO_2 conversion over a prolonged 30-h TOS at 700 °C. Chotirach et al. (2020) investigated the use of metal nitrides, specifically titanium nitride (TiN), as a mixed support in conjunction with SBA-15 loaded with Ni (Ni/TiN–SBA-15). The sample containing 18 wt.% TiN on the TiN–SBA-15 support exhibited a prolonged catalyst lifetime while maintaining 70 % CO_2 conversion over a reaction time of 4 h. This performance can be attributed to the surface basicity of TiN, which reduces carbon deposition on the catalyst.

Another research theme was the addition of bimetallic or doping metal species to the catalyst to mitigate the deactivation of the main active species (Chaisamphao et al., 2021; Kuboon et al., 2022; Sumarasingha et al., 2021). A study by Sumarasingha et al. (2021) revealed that 1 wt.%ZrO_2-doped 10 wt.% Ni/Al_2O_3 provided the highest CO_2 conversion of 50 % over a 10-h reaction time at a relatively low temperature of 620 °C. This result was attributed to the presence of a moderate number of basic sites from ZrO_2 that helped facilitate CO_2 transfer during the DRM reaction. In contrast, the bimetallic Ni–ZrO_2 and Ni/ZrO_2 catalysts exhibited poor catalytic performance because of their incompatible interactions. An interesting study on supported bimetallic Ni–Co by Kuboon et al. (2022) achieved a high catalytic performance of 90 % CO_2 conversion over a prolonged 120 h. This performance can be explained by the improved physiochemical properties

resulting from alloy formation between Ni and Co, combined with the surface defects of the boron nitride nanosheet support and its basicity, which facilitated the removal of carbon species from the catalyst surface.

Despite advancements in the physicochemical properties discussed in many studies, future perspectives on catalyst development in Thailand still lack investigations involving actual feed compounds (such as biogas or flue gas) and pilot-scale testing. Furthermore, most catalysts in Thailand exhibit relatively low activity and short reaction times, which do not reflect their catalytic stability compared to those from global studies and expected commercial applications. Therefore, further research on these issues is essential before catalytic CO_2 use can be implemented on an industrial scale.

2.3.3 Biochemical and biofuel production

Thailand possesses abundant biomass resources that are crucial to the country's strategy for developing biochemicals and biofuels. With plentiful agricultural resources and strong commitment to renewable energy, Thailand is well-positioned to become a leader in bio-based energy. The major types of available biomass include agricultural residues (such as rice husk and straw, sugarcane bagasse and molasses, cassava residues, and palm oil residues), wood and forestry residues (such as sawdust and wood chips), municipal solid waste (MSW), organic waste, and energy crops. Successfully using biomass products derived from agricultural feedstock to replace fossil fuels would strongly support the sustainable bioeconomy and biorefinery industries worldwide. An overview of biochemical and biofuel production is illustrated in **Fig. 7**. Up to 2024, the state-of-the-art technology for transforming biomass into biochemicals and biofuels involves biomass fractionation into cellulose, hemicellulose, and lignin. These three major components are then separately converted into intermediate chemical molecules that can be further upgraded to biofuels or fine biochemical products. Currently, available technologies include catalytic hydrolysis/hydrogenation, solvolysis, hydro-liquefaction, fast pyrolysis, and gasification with hydrogenation over conventional multifunctional solid catalysts.

i) Biochemical production

Biochemicals are derived from sugar platforms obtained from biomass (such as agricultural waste or cellulosic materials) using catalysts through various pathways, depending on the type of feedstock and the desired product. This process is part of a broader field of biorefinery, which replaces petroleum-based chemicals with renewable, bio-based alternatives. Heterogeneous catalysts play a key role in converting sugars like glucose or fructose into a wide range of platform chemicals such as 5-hydroxymethylfurfural (HMF), furfuryl alcohol, lactic acid, levulinic acid, and γ-valerolactone (GVL). They serve as building blocks for biodegradable plastics, biofuels, solvents, resins, and other bio-based materials (Kiatphuengporn et al., 2020; Lawagon et al., 2021; Songtawee et al., 2023; Tanwongwan et al., 2019; Termvidchakorn et al., 2017). Metal-based solid catalysts, such as metal oxides, zeolites, or supported metals, demonstrate high activity and are easy to recover and reuse. Several research groups in Thailand are continuously developing catalysts and fine-tuning reaction conditions for biochemical production.

A representative overview of the biochemical production is as follows: HMF has been produced through the dehydration of fructose and glucose and hydrolysis/dehydration of cellulose in hot compressed water (HCW) using catalysts such as calcium phosphate (CaP_2O_6) and strontium polyphosphate ($Sr(PO_3)_2$) (Daorattanachai et al., 2012), sulfonated magnetic carbon NPs (SMCNs) (Le et al., 2021), and Lewis acid NaY zeolite (Boonyoung et al., 2024). The highest HMF yields of 34–57 % were achieved

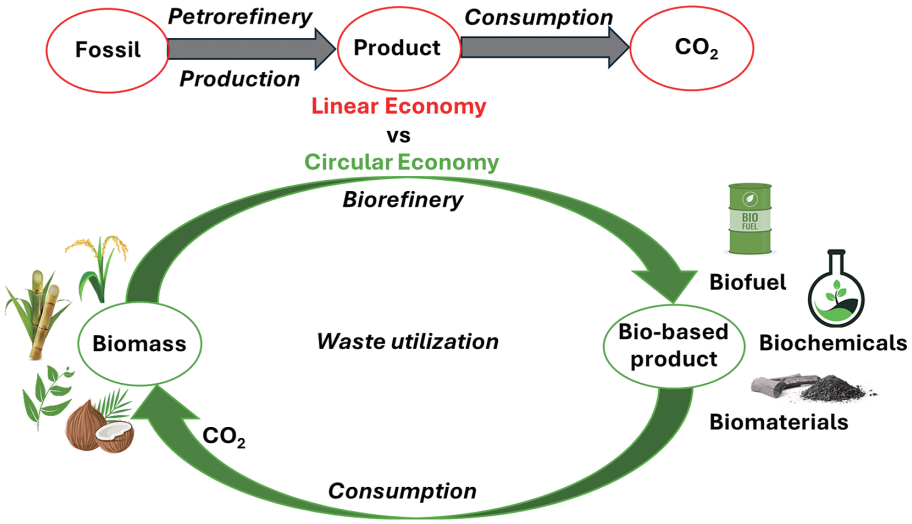

Fig. 7 Overview of biochemical and fuel production.

at 120–220 °C, with >80 % fructose and glucose conversion. Furfuryl alcohol (FOL) can be produced via the liquid-phase hydrogenation of furfural (FF) using Cu-based catalysts like Cu–Al spinel-oxide ($CuAl_2O_4$) (Intana et al., 2023; Thongratkaew et al., 2021) and Cu–Fe catalysts (Kalong et al., 2022). These catalysts demonstrated activity superior to other non-noble metal catalysts, achieving over 96–99 % FF conversion, >90 % FOL yield, and excellent stability. For lactic acid production, gamma-alumina (γ-Al_2O_3) with its large surface area, high stability, low cost, and abundance of Lewis acid sites, would be an effective support for converting sugar into lactic acid (Kiatphuengporn et al., 2020). Additionally, metal oxides such as Cr, Cu, Co, Ni, and Sn oxides doped on γ-Al_2O_3 enhanced lactic acid production (Kosri et al., 2021), achieving nearly 100 % conversion efficiency and a lactic acid yield of 63–74 % at 170 °C. GVL, an important organic compound used as a key building block for renewable chemicals and biofuels, can be produced from methyl levulinate (ML) conversion. Cu-based catalysts, particularly CuNiO (Tanwongwan et al., 2019) and Ni–Cu/SBA-15 (Fang et al., 2020), showed high ML conversion (>91 %) and high selectivity toward GVL (>89 %) within 3 h at 140–200 °C using 2-propanol or 2-butanol as a solvent. Further research on biochemical production is provided in **Supplementary S5**.

ii) Biofuel production

The catalytic process enhances the efficiency and sustainability of biofuel production by enabling the use of various feedstocks, improving yields, and reducing production costs. There is a growing focus on developing more effective catalysts, optimizing reaction conditions, and introducing technologies to overcome current challenges and improve the economic feasibility of biofuels in Thailand. Biofuels, mainly biodiesel, are produced from vegetable oils (such as palm oil) and waste cooking oils through transesterification. In this process, triglycerides in oils react with alcohol (usually methanol) in the presence of a catalyst to form fatty acid methyl esters (FAME) or biodiesel, with glycerol as a by-product.

Thailand's research in biodiesel production explores the use of heterogeneous catalysts such as Ca- or Ni-supported catalysts. Ca-based catalysts, particularly CaO, have gained significant attention for biodiesel production via transesterification due to their high activity, reusability, low cost, and environmental friendliness. For example, Samart et al. (2010) demonstrated that biodiesel produced through the transesterification of soybean oil over CaO supported on mesoporous silica met all biodiesel standards in Thailand. The process achieved a maximum conversion of 95.2 % at 60 °C with a reaction time of 8 h, Ca loading of 15 wt.%, and a catalyst-to-oil ratio of 5 % (w/w). Witoon et al. (2014) used bimodal meso-macroporous silica as a support to enhance the accessibility of CaO dispersed within the pores. The CaO-loaded bimodal porous silica catalyst achieved a high FAME yield of 94.2 % in the first cycle and maintained excellent performance even after five cycles. A low-cost, eco-friendly CaO catalyst can be synthesized from waste eggshells by calcinating $CaCO_3$ to produce CaO. Viriya-Empikul et al. (2012) prepared CaO catalysts derived from eggshells, golden apple snail shells, and meretrix venus shells for biodiesel production. CaO catalysts obtained from eggshell at a calcination temperature of 800 °C demonstrated high activity, achieving 94.1 % FAME yield within 2 h. Khemthong et al. (2012) also investigated the activity of CaO derived from eggshell waste for biodiesel production via transesterification of palm oil with CH_3OH under microwave conditions. The use of microwave irradiation significantly accelerated the transesterification reaction compared with conventional heating. The optimal conditions yielded a maximum FAME production of 96.7 %, which was achieved with a reaction time of 4 min, microwave power of 900 W, methanol-to-oil ratio of 18:1, and catalyst loading of 15 %.

In addition, Ni-based catalysts offer a promising option for biodiesel production due to their cost-effectiveness, high catalytic activity, and ability to facilitate both hydrogenation and transesterification processes. Srifa et al. (2014) studied the effect of reaction parameters on hydrotreating palm oil to produce bio-hydrogenated diesel (BHD) over a $NiMoS_2/\gamma$-Al_2O_3 catalyst. The optimal conditions were a temperature of 300 °C, a pressure of 50 bar, a liquid hourly space velocity (LHSV) of 1 h^{-1}, and an H_2/oil volume ratio of 1,000:1 (cm^3/cm^3 at NTP conditions). Under these conditions, the product yield reached 90 % and the n-alkane content exceeded 95.5 %. Additionally, Srifa et al. (2018) also tested the reaction using a $NiAl_2O_4$ spinel-type catalyst. The highest triglyceride conversion (~100 %) and product yield of 94.3 % were achieved for $NiAl_2O_4$ reduced at 650 °C. Notably, the spinel-type catalyst exhibited high stability over 24 h on stream, whereas significant degradation was observed with the reference catalyst, Ni-supported on γ-Al_2O_3. The superior performance of the $NiAl_2O_4$ spinel-type catalyst was attributed to the well-dispersed metallic Ni species and the highly stable spinel structure. Rakmae et al. (2020) prepared Ni phosphide on mordenite zeolite in the sodium form (Ni–P/NaMOR). The highest hydrodeoxygenation (HDO) yield and selectivity toward C_{15}–C_{18} alkanes (83.5 %) over this catalyst was obtained at the optimum condition of 425 °C and 50 bar. Ruangudomsakul et al. (2021) demonstrated that Ni_2P-supported AC derived from wood exhibited outstanding performance in the HDO of palm oil, achieving a remarkable green diesel yield of 98.3 %. The superior performance was likely due to the enhanced accessibility of reactants to the active sites on the catalyst.

In conclusion, many research efforts in Thailand have focused on converting biomass to value-added products,

particularly biodiesel. The researchers explored various feedstocks and catalysts to improve efficiency and sustainability. This includes using waste oils, such as used cooking oil and animal fats, and innovative catalysts like CaO derived from waste materials. In addition, microwave-assisted transesterification and supercritical fluid methods were investigated to boost biodiesel yields and reduce production costs. These initiatives supported Thailand's renewable energy goals and foster a more sustainable biofuels industry. However, the development of highly efficient, easy-to-implement, and cost-competitive processing technologies for large-scale biomass conversion remains inadequate. Several significant technological barriers remain to be addressed. Therefore, it is essential to tackle the challenges associated with advancing technologies for the cost-competitive production of biochemicals and biofuels with scalability.

3. Impacts on Thai academia, society, and economy

Nanotechnology (NT), including NPT, has had profound impacts on Thai academia, society, and the economy, fostering innovation, enhancing capabilities, and contributing to economic growth. As the brainchild of Dr. Pairash Thatchayapong, then President of NSTDA, NANOTEC was established in 2003 with Dr. Wiwut Tanthapanichakoon as its first Executive Director. It has played a crucial role as a catalyst for the creation and acceleration of NPT alongside NT in Thailand, ranging from raising societal and industrial awareness of NT, promoting multidisciplinary research and multilateral collaboration across departments and institutions, and contributing remarkable impacts to Thailand's economy. For example, it stimulated the launch in 2005 of the first undergraduate-level Nano Engineering program (NANO), a multidisciplinary scheme offered by Chula International School of Engineering (ISE) to develop and produce world-class international engineers who are equipped with cutting-edge skills and knowledge to address global and local challenges. Similarly, NANOTEC stimulated the establishment of the College of Nanotechnology at KMITL in 2008. In addition, many existing graduate programs in the Faculties of Science and Engineering across the country have also consciously promoted research related to nanotechnology. Unfortunately, there is no reliable data on NPT-related undergraduate and graduate students produced nationally.

According to Dr. Weeraya Khunkaew of NANOTEC, since its inception in 2003 until March 2024, NANOTEC has produced 1,530 international publications, 102 industrial prototypes (50 % of which were launched), 1,088 patent applications (555 granted), and received 300 international/national awards. Regarding its estimated accumulative economic impacts, NANOTEC has induced 5,465 million Thai Baht in science and technology (S&T) investments and 42.868 million Thai Baht equivalent in socioeconomic impacts. Note that these data belong to nanotechnology in general and are not limited to NPT.

4. Conclusion

NPT covers a wide variety of disciplines, subject areas, and industries, not to mention nanomaterials and even nanotechnology. Therefore, this review focuses mainly on the health and well-being fields (biosensing, drug delivery, therapeutics) unavoidable by Thailand's aging society and CCU (CO_2 adsorption, CO_2 utilization) needed to counter global climate change, which is necessary and essential for achieving carbon neutrality in 2050.

To ensure a sustainable future, Thailand's researchers, including NANOTEC, must continue to leverage its achievements while addressing emerging challenges. By focusing on industry collaboration, international competitiveness, green nanotechnology, and public engagement, Thailand can become a recognized global player in nanotechnology, reaping significant socioeconomic and environmental benefits.

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Supplementary Information

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Nomenclature

APPIE	Association of Powder Process Industry and Engineering, Japan
ASEAN	Association of Southeast Asian Nations
BCG	bio-circular-green
CCU	carbon capture and utilization
CEPT	Center of Excellence in Particle Technology
CoE	center of excellence
CU	Chulalongkorn University
DRM	dry reforming of methane
GNP	gold nanoparticle
GNR	gold nanorod
KMITL	King Mongkut's Institute of Technology Ladkrabang
ML	machine learning
MNP	magnetic nanoparticle
MRI	magnetic resonance imaging
MS	mesocellular silica
MWCNT	multi-walled carbon nanotube
NANOTEC	National Nanotechnology Center

NNI	National Nanotechnology Initiative
NP	nanoparticle
NPT	nanoparticle technology
NSTDA	National Science and Technology Development Agency
PLGA	poly(D,L-lactide-co-glycolide)
PT	particle technology
RNN	research network of NANOTEC
SERS	surface-enhanced Raman scattering
SLRI	Synchrotron Light Research Institute
SPECT	single photon emission computed tomography
SPTJ	Society of Powder Technology, Japan
TNP	titanate nanoparticle
TNT	titanate nanotube
TNW	titanate nanowire
TPTC	Thai Powder Technology Center
TRF	Thailand Research Fund

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