

Unleashing the Contribution of Nanoparticles in Reforming Low-Carbon Solutions: Current Status, Trend, and Prospects

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Abstract

The alarming climate change that has occurred on Earth has increased the urgency of reducing global CO₂ emissions. In response to this longstanding issue, many countries and organizations have been actively strengthening the implementation of low-carbon strategies as a crucial step toward achieving the larger goal of net-zero carbon emissions by 2050. Nanoparticles, extremely tiny particles with at least one of their dimensions ranging from 1 nm to 100 nm, played a significant role in advancing diverse low-carbon technologies. While it was not emphasized previously, the present article serves as the first note to look into the utilization of this unique matter, specifically in (i) carbon capture and storage (CCS) technology, (ii) catalytic conversion and upcycle of CO₂ into value-added fuels and chemicals, (iii) the development of low-carbon and carbon-neutral fuels with improved combustion properties, (iv) the enhancement of low-carbon energy harvesting technology, (v) the development of lithium-ion batteries for low-carbon mobility, and their applications in (vi) improved crude oil extraction technology. Nanoparticles have gained favour in low-carbon technologies primarily because of their significantly larger specific surface area, which leads to better interfacial interaction, reactivity, adsorption capacity, sensitivity, and other properties. Here, the status and progress in the aforementioned nanoparticle-enabled low-carbon technologies are discussed and reviewed. Considering that it is essential to attain carbon neutrality in the long run, the future outlook in this study area is proposed to be focused on the pursuit of manufacturing/synthesis of nanoparticles in an environmentally friendly, reduced carbon footprint manner. It is envisaged that this study will offer a holistic view as well as new insights into the role of nanoparticles in paving the way towards a low-carbon future.

Keywords: Carbon Footprints, Carbon Capture and Storage, Low-Carbon Energy, Low Carbon Manufacturing, Nanotechnology, Nanoparticles

1.0 Introduction

Climate action has been an on-going hot topic for decades and has gained much intense attention recently in light of the need to take immediate action to combat the extreme weather. In this regard, many countries around the world are now emphasizing carbon reduction roadmap in their nation development plans in alignment with the two important global agendas, namely the Paris Agreement and the Net Zero Emissions by 2050 target [1, 2]. The reduction of carbon footprints (also known as low carbon) requires rapid development of low-carbon technologies through science and technology innovation. For instance, carbon capture and storage (CCS) technology, CO₂ conversion and upcycling technology, and technology for harvesting low-carbon energy are among the crucial science and technology innovations needed for a successful low-carbon progress. Interestingly, a keyword search for "Low Carbon" OR "Net Zero Emission" OR "Net Zero Carbon" within the Scopus database returned 144106 document counts based on subject area, with the majority of them falling under the categories of Engineering (23.6%), Material Science (15.7%), Energy (11.1%), Environmental Science (10.8%), and so on. Apparently, it appears that the discussion on science and technology innovation used to advance the low-carbon progress is worthy of a detailed study.

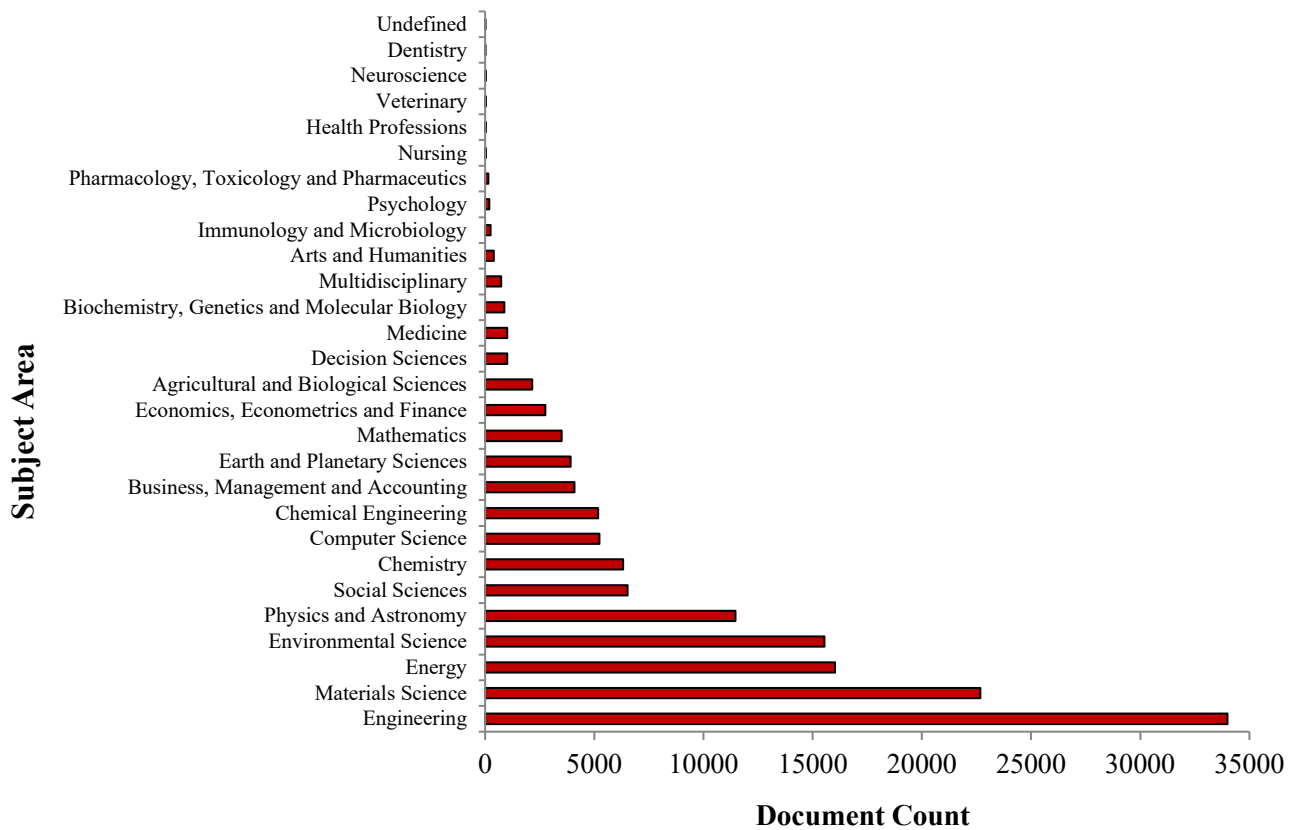


Figure 1. Boolean searching on the topic "Low Carbon" OR "Net Zero Emission" OR "Net Zero Carbon" within article title, abstracts, or keywords. Note that 70000 documents were retrieved; each of which has been assigned to one or more subject areas, hence the total number of document count based on subject area is higher. [Scopus database as of 30th September 2023].

One of the emerging subfields of science and technology innovation is ‘Nanotechnology’ which has revolutionized various industries enormously [3]. As a general guideline, this technology deals with nanoparticles, which are particles with at least one of the dimensions fall within the nano-range (*i.e.* < 100 nm) [4]. Depending on the number of dimensions that fall within the nano-range, nanoparticles are further categorized into 0-D, 1-D, 2-D, and 3-D. The unique features of this matter lie in its tiny size, which grants a high specific surface area (or surface area-to-volume ratio) and better characteristics

(such as thermal, magnetic, catalytic, mechanical, optical, and electrical) that are unattainable by the bulk counterparts [5, 6]. Since the classic talk by Richard Feynman's in December 1959 on the topic "There's Plenty of Room at the Bottom", the application of nanoparticles has been booming and is becoming a norm in electrical and electronics industry [7], biomedical industry [8, 9], oil and gas industry [10], food supply chain industry [11, 12], environmental engineering application [13, 14], and many more.

In addition to the aforementioned applications, the use of nanoparticles to enable the expansion of low-carbon progress is a promising area of study. In fact, from lab-scale testing to industrial-scale implementation, nanoparticles have been playing an important role in advancing various low-carbon technologies. While it was not emphasized previously, this article serves as the first note to unleash the contribution of nanoparticle technology in low-carbon development. This paper focuses on several demanding technologies, including CCS technology, technology for transforming CO₂ molecules into other value-added products, technology to improve the combustion properties of low-carbon and carbon-neutral fuels, technology for enhancing renewable energy (low-carbon energy) harvesting systems, battery technology for electric vehicles, and improved technology for crude oil extraction. Furthermore, future prospects in this field of study are suggested, driven by the pursuit of achieving carbon neutrality in the long run.

2.1 As Sorbent for Carbon Capture and Storage (CCS)

CCS is a crucial technology in decarbonization [15]. The Intergovernmental Panel on Climate Change (IPCC) has indicated that achieving global climate goals is challenging without the implementation of CCS [16]. Various nanoparticles have been proven to work

well at the laboratory stage to achieve the CCS [17]. The mentioned nanoparticles may range from carbon-based, silica-based, zeolite-based, polymer-bearing nanoparticles, as well as metal (hydr)oxides-based materials [17-21]. The following sections describe the application of nanoparticles in both carbon capture and carbon storage applications.

2.1.1 Nanoparticles in Carbon Capture

Diverse emerging materials have been designed to attain CO₂ capture during pre-combustion, post-combustion, and oxygen-enriched combustion processes [22]. CO₂ capture using nanoparticles can be done either by using (i) dried nanopowder or (ii) nanofluid. The former is typically accomplished by selectively adsorbing CO₂ gas from a mixture of gases onto the nanopowder, while the latter involves the absorption of CO₂ gas into a liquid medium containing dispersion of nanoparticles (also known as nanofluids). Figure 2 illustrates the differences between both carbon capture strategies using nanoparticles.

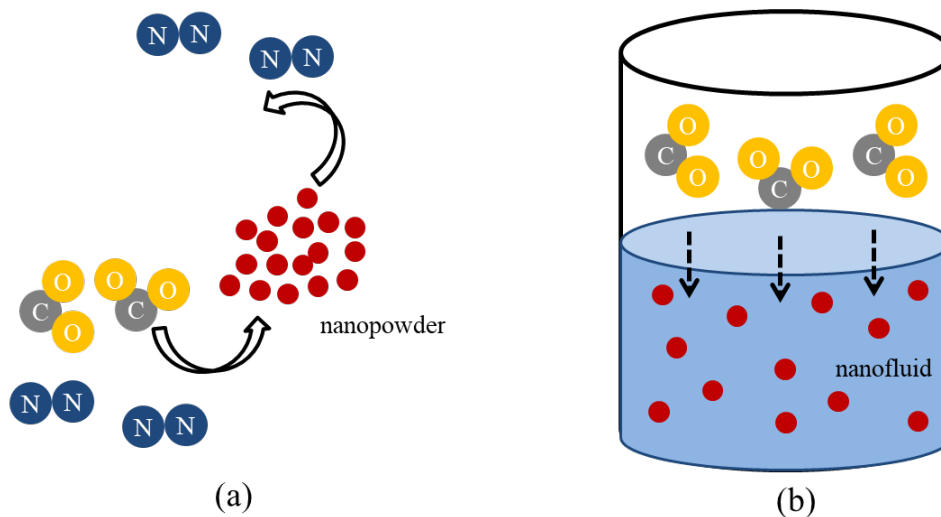


Figure 2. Schematic diagram showing (a) the uses of nanopowder for adsorption of CO₂ from gas mixture, and (b) the uses of nanofluid for absorption of CO₂ gas.

Selective adsorption of CO₂ from a mixture of gases onto nanopowder depends on the intermolecular forces between the molecules of CO₂ and the surface of the solid nanoparticles [22]. Particularly, nanoparticles with surface basicity favor high-selectivity adsorption of CO₂, an acidic gas [23]. In terms of structural contribution, the nano-scaled entity offers a decrement in the diffusion path length which promote the diffusion of CO₂ into the pores of the adsorbent [24]. Hence, research has found that decreasing the adsorbent size from micron-scaled to nano-scaled can lead to a significant improvement in CO₂ adsorption capacity [25]. To further enhance the CO₂ capture capacity, the surface of the nanoparticles is modified with desired functional groups. For instance, multiwalled-carbon nanotubes (MWCNTs) modified with N¹-(3-trimethoxysilylpropyl)diethylenetriamine (DETASi) were found to exhibit enhanced CO₂ capture capability due to the interaction between CO₂ molecules and the amine group of DETASi [26]. To further reduce carbon footprints, utilization of nanoparticles produced from agricultural wastes for CO₂ capture has recently gained much attention. Valdebenito et al. demonstrated cellulose nanofibrils extracted from corn husks, oat hulls, and kraft pulp able to adsorb 0.90, 1.27, and 2.11 mmol CO₂/g upon modification with diaminosilane N-[3-(Trimethoxysilyl)propyl]ethylenediamine [27]. On the other hand, Mohd et al. extracted nanocrystalline cellulose (NCC) from the fiber of oil palm biomass for CO₂ adsorption [28]. Their study showed that about 0.10 mmol CO₂/g of adsorption capacity was achieved by using neat NCC; meanwhile, aminosilane-modified NCC exhibited a twofold increase in adsorption capacity due to the reaction between the amine group and CO₂ molecules. Table 1 lists several reported works on the application of nanoparticles for carbon capture through adsorption onto nanopowders.

Table 1. Reported works on the application of nanoparticles for carbon capture (through adsorption onto dried nanopowders).

Nanoparticle	Capture technology	Operating temperature	CO₂ capture Capacity	Ref.
Modified organosilica nanoparticles	Adsorption was studied using micromeritics 3Flex device	273 K	2.26 mmol/g	[29]
Functionalized MWCNTs	Adsorption onto MWCNTs powder was studied using thermogravimetric analyser	308 K	0.17 - 0.43 mmol/g	[26]
Nanocrystalline cellulose (NCC)	Adsorption onto NCC aerogel contained in packed column	298 K	0.10 - 0.20 mmol/g	[28]
Graphene-based monoliths	Adsorption onto the monoliths was studied using Micromeritics ASAP 2020 Analyzer	298 K	2.1 mmol/g	[21]
Fe ₃ O ₄ nanoparticles/Graphene oxide	Adsorption onto the nanocomposite was studied using high pressure sorption analyzer	300 K	2.3 mmol/g	[30]
Functionalized Cellulose nanofibril	Adsorption onto cellulose nanofibril film	298 K	0.90 - 2.11 mmol/g	[27]
Zeolite nanoparticle	Adsorption onto zeolite nanoparticle loaded in an adsorption cell	288K	6.536 mmol/g	[25]

Compared to CO₂ adsorption by nanopowder, CO₂ absorption by nanofluids has been more frequently studied. Nanofluid is prepared by dispersing selected nanoparticles in a liquid absorbing medium; study has found that the additions of nanoparticles can intensify the CO₂ absorption by over 70 % [31]. Fundamentally, the capturing of CO₂ by nanofluid was governed by a few possible mechanisms [32-37]: (1) the Brownian motion of nanoparticles develops micro-convection in the nanofluid which eventually increases the CO₂ diffusion from the air region to the nanofluid region; (2) the Shuttle effect promoted by the ability of nanoparticles to adsorb CO₂ in the gas-liquid interface and later on transport the adsorbed CO₂ to the liquid medium; (3) the Bubble breaking effect in which the irregular motion of the nanoparticles in the fluid causes to the breaking of gas bubbles into smaller bubbles, the surface contact among gas and liquid phase increases and CO₂ solubility was enhanced. Such unique CO₂ absorption mechanisms imposed by the presence of nanoparticles make nanofluid more promising than conventional amine-based absorbing mediums. For instance, Liang et al. reported that nanofluid (TiO₂ nanoparticles dispersed in methyldiethanolamine (MDEA) and monoethanolamine (MEA)) outperformed pure amine solvents in CO₂ absorption; the enhancement factor may reach up to 1.36 by employing 25% MDEA cum 5% MEA nanofluids as the absorbing medium [38]. Efficiency of the CO₂ absorption process is further affected by the loading amount, size, and types of the nanoentity used [39]. Table 2 lists several reported works on the application of nanoparticles for carbon capture through absorption into nanofluids.

Table 2. Reported works on the application of nanoparticles for carbon capture (through absorption into nanofluids).

Nanoparticle	Base Fluid	Amount of nanoparticles added	Capture technology	Enhancement of CO ₂ capture as compared to neat base fluid	Ref.
TiO ₂ nanoparticles	30 wt% 3,3- Iminobis (N,N-dimethylpropylamine)/50 wt% Dimethyl ether/20 wt% Water	0.03-0.12 wt%	Direct absorption into nanofluids using continuous absorption column	31.4 %	[40]
SiO ₂ nanoparticles		0.03-0.12 wt%		14.3 %	
TiO ₂ nanoparticles	Choline chloride-ethylene glycol	0.6 kg/m ³	Direct absorption into nanofluids using a stirred cell	~ 1.34 of enhancement factor ^a	[39]
Al ₂ O ₃ nanoparticles	Water	0.025 %v/v	Direct absorption into nanofluids using laboratory-scale wetted wall column	Increase by 3.22 times (from 25.55 g CO ₂ absorbed improved to 82.42 g)	[41]
TiO ₂ nanoparticles		0.6 g/L		~ 1.20 of enhancement factor	
Al ₂ O ₃ nanoparticles	MDEA	0.8 g/L	Direct absorption into nanofluids	~ 1.13 of enhancement factor	[42]
SiO ₂ nanoparticles		0.8 g/L		~ 1.06 of enhancement factor	
TiO ₂ nanoparticles		0.1 wt%	Direct absorption into nanofluids conducted in a high-pressure vessel	39.81 % RAI ^b	[43]
Al ₂ O ₃ nanoparticles	Water	0.14 wt%		22.30 % RAI	
ZnO			Absorption	59 %	

nanoparticles			was governed by hollow fiber membrane contactor assisted by nanofluids		[44]
TiO ₂ nanoparticles	Water	0.15 wt %		34 %	
MWCNTs				50 %	
Fe ₃ O ₄ nanoparticles	Water	0.001 % by vol.	Direct absorption into nanofluids assisted by external electric field	Not reported	[45]
SiO ₂ nanoparticles		0.10 wt%		21 %	
Al ₂ O ₃ nanoparticles		0.10 wt%	Direct absorption into nanofluids	18 %	[32]
Fe ₃ O ₄ nanoparticles	Water	0.02 wt%		24 %	
CNTs		0.02 wt%		34 %	
CNTs	MDEA	0.02 wt%	Direct absorption into nanofluids	23 %	[32]

^a Enhancement factor = $\frac{V_{co2-nanofluid}}{V_{co2-base fluid}}$, under similar fluid dynamic conditions.

^b Relative absorption index = $\frac{Absorption\ capacity_{nanofluid} - Absorption\ capacity_{water}}{Absorption\ capacity_{water}}$

2.1.2 Nanoparticles in Carbon Storage

Besides carbon capture, carbon storage also plays a prominent role in advancing low-carbon development. Carbon storage, also known as carbon sequestration, refers to the long-term keeping of the captured CO₂ in underground environments, deep-sea sediments, and other types of reservoirs [46, 47]. The distinctive huge specific surface area of nanoparticles makes them promising candidates for storing CO₂. In fact, the technology of using tiny

particles for CO₂ storage is not new but was explored decades ago. In 1997, researchers have showed that CO gas can be intercalated with fullerene particle at the ratio of 1:1; this phenomenon was proven by the gradual transition of the CO gas molecules from free motion state (at room temperature) to almost restricted motion state (at low temperature) [48]. On the other hand, in 1988, Gadd et al. demonstrated that CO₂, in stoichiometric amounts, can be forced into the lattice of fullerene particles through the Hot Isostatic Pressing method. The stored CO₂ was found to gradually escape into the environment during the first 1500 hours but become more stable over time (less losing of CO₂) [49]. Although not mentioned in either of the articles, fullerenes, C₆₀, are chemically active particles that can be reduced to the nano-range through optimization of the synthesis process [50, 51]. Similar to C₆₀, graphene nanosheet and CNTs are another two types of carbon-based nanoparticles used for carbon storage application [15, 52-54]. In addition to their high specific surface area, nanoparticles with high porosity also possess a considerable capacity to lock-in CO₂ molecules [15, 55].

A recent review by Youns et al. reported that various nanoparticles have been proven to enhance carbon adsorption capacity. In particular, incorporating selected nanoparticles, such as SiO₂ and TiO₂ nanoparticles, may alter the physicochemical properties of shale and sandstone, subsequently affecting the capacity for geological sequestration of CO₂ [15, 56]. Yekeen et al. discovered that under a typical geo-storage conditions (353 K and 25 MPa), the contact angle of shale treated with 0.1 wt% SiO₂ nanoparticles/0.2 wt% saponin surfactant reduced (become more water-wet) and such reduction was amplified with the increases of nanoparticle dosage [56]. Identically, Al-Yaseri et al. reported that the basalt surface turns weakly water-wet upon treated with SiO₂ nanoparticles; the contact angle reduced with the increases of SiO₂ nanoparticle dosage from 100 mg/L to 2000 mg/L [57]. The water-wet property is desirable as it leads to better sealing capacity, a greater potential for the containment of CO₂, as well as the effective integrity of the geological storage sites [58].

A fascinating study published recently by Mishra et al. showed that adding graphene oxide nanoparticles into cementitious system can be utilized for CO₂ sequestration; the CO₂ uptake was significantly improved (by 30 %) by just adding a mild amount (0.05 %) of graphene oxide [52]. CO₂ molecules react with calcium ions when diffuses into the cement matrix that containing graphene oxide, which subsequently leading to the formation of carbonate ions (CO₃²⁻). The graphene oxide nanoparticles, which turns positive charge upon attached with calcium ions, are favourably attracting more carbonate ions. In fact, the idea of attaining CO₂ fixation by carbonation reaction is an emerging strategy to achieve net zero emission in the cement manufacturing industries.

2.2 As Catalyst for Conversion of CO₂ to Valuable Products

In addition to CCS, researchers have advanced the low-carbon development by converting CO₂ into value-added products such as fuels, combustible compounds, and chemicals [59-61]. Such conversion is normally facilitated by a catalyst; nano-scaled catalysts, in particular, have gained much attention as they offer multiple catalytic reaction sites owing to the huge specific surface area [62, 63]. In addition, their uniquely small sizes allow the nano-catalysts to be well-dispersed within the reaction medium (whether in gas or liquid phase), thereby promoting a better reactivity. Table 3 lists several recent works on the utilization of nanoparticles as catalysts for conversion of CO₂ to value-added products.

Table 3. Reported works on conversion of CO₂ gas to value-added products over nanocatalysts.

Carbon source	Nanocatalyst (size)	Method of incorporating the nanocatalyst	Catalysis Reaction	Final Product	Ref.
CO ₂ gas	Cu	Cu nanoparticle-	Electroreduction	Ethanol,	[64]

	nanoparticles (7 – 18 nm)	deposited carbon paper was used as the working electrode. Pt wire was used as the counter electrode.		propanol, ethylene	
CO ₂ gas	Pt nanoparticles supported on Sr ₂ Nb ₂ O ₇ nanosheets	Pt nanoparticles was deposited on the surface of Sr ₂ Nb ₂ O ₇ nanosheets and spread on a glass dish	Photothermal reduction	Methane	[65]
CO ₂ gas	Au nanoparticles	3 mL of the Au nanoparticles (~100 mg/L) was dried before uniformly distributed in a reaction chamber.	Photothermal reduction	Carbon Monoxide	[66]
CO ₂ gas, and CO gas	TiO ₂ nanoparticles supported on Ni	The nanocatalysts were used in a fixed bed reactor where the gas feedstock was introduced at constant flow rate.	Photo-assisted Methanation	Methane	[67]
CO ₂ gas	Ru nanoparticles supported on Ti nanotubes	100 mg of Ru/Ti nanotubes catalysts were added to a sealed batch reactor. Later on, H ₂ and CO ₂ gases were introduced into the reactor through purging.	Photothermal reduction	Methane	[68]
CO ₂ gas	Ru nanoparticles	0.04 g of Ru nanoparticles was dispersed in ionic liquid phase	Hydrogenation	Methane	[69]
Dissolved CO ₂	Cu nanoparticles (30 – 100 nm)	Cu nanoparticles was deposited on graphene electrode	Electroreduction	Ethanol	[63]

One exciting example is the recent work reported in *Nature* whereby active Cu nanoparticles was used to catalyse the electroreduction of CO₂ into renewable fuels and chemicals which include ethanol, propanol, ethylene, and other multi-carbon products [64]. The study was done to examine the change in the active sites of the Cu nanocatalysts during the reaction through a combination of time-resolved *operando* techniques and 4D-electrochemical liquid-cell scanning transmission electron microscopy. Results showed that the Cu nanocatalysts, with size ranging from 7 nm to 18 nm, evolved into active Cu nanograins during the CO₂ electrolysis process; the oxide layer of the nanocatalysts degraded, generating new sites for CO₂ molecules to attach and converted to the multi-carbon products. Because of size variations, the 7 nm Cu nanoparticle assembly, with a unity fraction of active Cu nanograins, demonstrates C₂₊ selectivity of sixfold higher than 18 nm Cu nanoparticle. This fascinating research outcome has spotlighted the potential of converting the unwanted CO₂ gas into energy, governed by the distinctive structural properties of the nanocatalyst.

In another study, the conversion of CO₂ into ethanol over Cu nanoparticle/N-doped graphene electrode was proven by Song et al. In their study, direct electrochemical conversion of dissolved CO₂ to ethanol was successfully achieved at high Faradaic efficiency (63 %) and high selectivity (84 %) under the presence of the nanocatalyst [63]. Here, the Cu nanoparticles of size 30 - 100 nm were deposited on an N-doped graphene electrode through electrochemical method; the Cu nanoparticle/N-doped graphene electrode was then employed as the working electrode (with platinum as the counter electrode) for electroreduction of dissolved CO₂ into ethanol.

Among the metallic elements usually used for catalysis application, ruthenium (Ru) has been regarded as one of the most active and stable metals that require lower reaction temperatures [70]. Melo et al. utilized Ru nanoparticles (2.5 nm in size) coupled with ionic liquid to catalyse the conversion of CO₂ gas into methane (CH₄). With the presence of this nanocatalyst, about 84 % of CH₄ yield was successfully achieved at low temperature (150 °C) (see Figure 3) [69]. Here, 0.04 g of Ru nanoparticles was dispersed in ionic liquid phase and two gases feedstock (namely CO₂ and H₂) were admitted to the catalysis medium for hydrogenation reaction. The reaction was done at 150 °C, 125 bar, and 24 hrs of constant stirring. The nanocatalyst was recycled and reused for up to five cycles, with a drop in CH₄ yield to around 60% on the 5th run. The reduction in conversion efficiency was attributed to the agglomeration of the nanocatalyst after multiple rounds of usage.

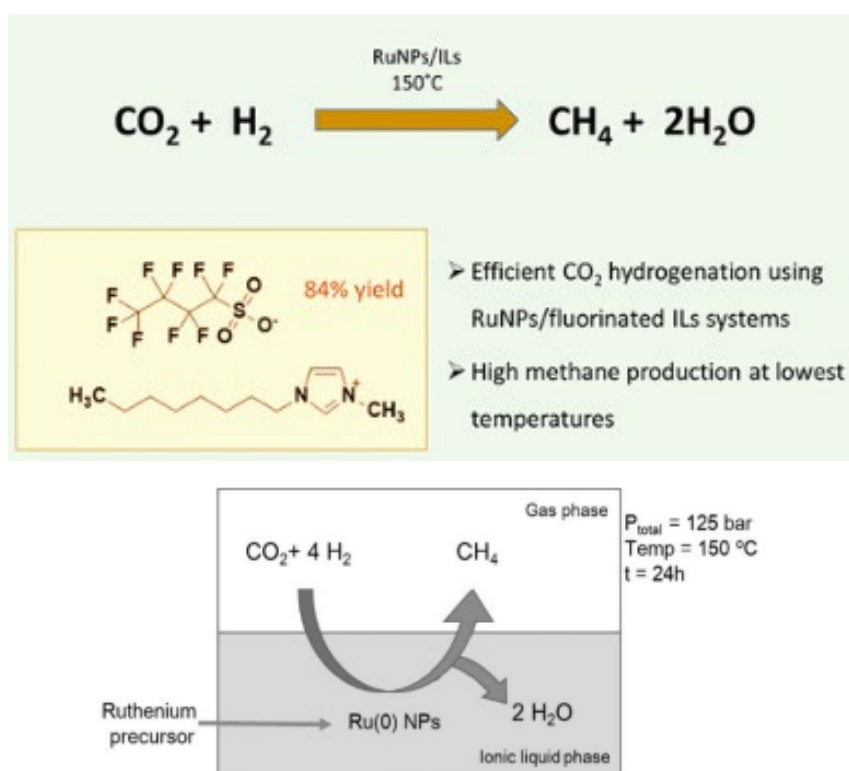


Figure 3. Schematic diagram showing the uses of Ru nanoparticles to catalyse the conversion of CO₂ to methane under fluorinated ionic liquid system [Reprinted with permission from [69], Copyright (2019) American Chemical Society].

To further progress toward a low carbon future, technologies like photothermal catalytic reduction of CO₂ over nanoparticles (using sunlight) are becoming increasingly important. In another words, the photothermal reduction process making uses of the synergistic effect from ‘sunlight’ energy and thermal energy for repurposing of the CO₂. In this application, nanocatalysts with plasmonic resonance properties act as an alternative to the conventional heating that requires elevated reaction temperatures [71]. Pan et al. attained an effective photothermal conversion of CO₂ to CH₄ (~100 % selectivity) over a Pt nanoparticles-deposited Sr₂Nb₂O₇ nanosheets [65]. The photothermal reaction was conducted under illumination of an artificial light (300 W xenon lamp in this case) for a period of 1 hr. The Pt nanoparticles and the Sr₂Nb₂O₇ nanoparticles create heterojunctions which enable the separation of photogenerated carriers and accumulation of photogenerated electrons on the Pt nanoparticles, thereby improving the catalytic efficiency and leading to optimal CH₄ yield (15.65 μmol/g/h). More reported works on photothermal conversion of CO₂ to value-added products catalysed by nanocatalysts are listed in Table 3.

In addition to ethanol and CH₄, conversion of CO₂ to methanol [72, 73], ethylene [74], propanol [75], and dimethyl Ether [76] have been recorded. Thanks to the high specific surface area of nanoparticles, the catalysis and conversion processes can be ran efficiently [59]. More interestingly, the activity and selectivity can be tuned based on the nanoparticle size [75]. This promising technology is crucial to be further developed and brought to industrial practice as a means of simultaneously addressing the pressing issues of CO₂ emissions - global warming, and the quest for alternative fuels [60].

2.3 As Additives to Enhance the Properties of Low-Carbon Fuels (LCFs) and Carbon-Neutral Fuels (CNFs)

Another emerging usage of nanoparticles is in the field of low-carbon fuels (LCFs) and carbon-neutral fuels (CNFs) development. Unlike gasoline and diesel, LCFs and CNFs are two classes of green fuels that emit less CO₂ upon combustion [77] or attain no net greenhouse gas emissions (*i.e.*, the release CO₂ which will be recaptured and reused for its' production) [78], respectively. LCFs and CNFs are essential substitutes to the conventional fossil fuels in order to reduce carbon footprints of the transportation industry [79]. Sustainable aviation fuel (SAF), bioethanol, and biodiesel are some of the known green fuels. Nevertheless, these green fuels are not without limitations. For instance, biodiesel suffers from a high potential for NO_x emissions, poor atomization, low cetane number which led to a longer ignition delay, and incomplete combustion [80, 81]. Such a drawback restricts the widespread application of green fuels. Despite this, it is interesting to note that researchers have managed to address and improve the mentioned concerns through the incorporation of nanoparticles. The nanoparticles are normally added to the fuel in very little extents ranging from few hundred ppm to a few thousand ppm [82].

Clean combustion is easier to be achieved through the blending of nanoparticles into LCFs and CNFs; in particular, the nanoparticle-enabled fuels exhibit a notable enhancement in the brake thermal efficiency, decrease in the ignition delay, decrease in the smoke opacity, as well as decrease in the emission of CO, NO, and hydrocarbon [83]. Such an enhancement was attributed to the role of nanoparticles as an oxygen buffer which provides additional oxygen for combustion, and improved spray atomization [83-85], as illustrated in Figure 4a. Furthermore, the high specific surface area of nanoparticles promotes heat transfer rates and allows more fuel to react with oxygen, thereby improve the combustion kinetics [83]. Also,

the catalytic behaviour of nanoparticles leading to a reduction in exhaust pollutants [84]. The seminal work by Prabu has proven that adding 30 ppm of Al_2O_3 (51 nm) and CeO_2 (32 nm) nanoparticles in biodiesel reduced the CO emission by 60 % and 77.78 % as compared to those emitted from the combustion of pure biodiesel and diesel, respectively [83] (Table 4). In terms of fuel properties, the $\text{Al}_2\text{O}_3/\text{CeO}_2$ nanoparticles-enabled B20 biodiesel exhibited the lowest ignition delay (4.5°CA) as compared to pure biodiesel (5.8°CA), and pure diesel (7.5°CA). This result implied that the nanoparticle-enabled LCFs or CNFs ignite more quickly after injection than the neat counterpart.

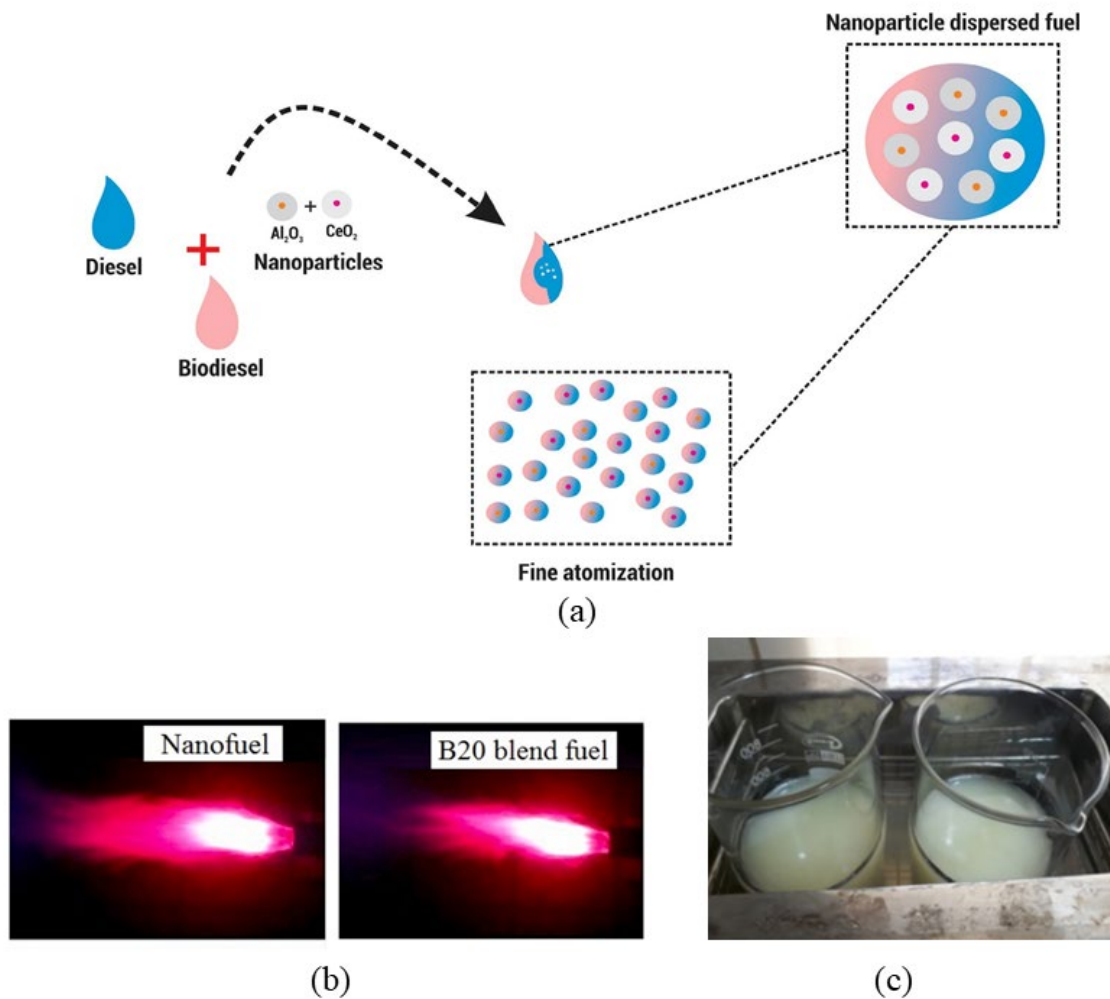


Figure 4. (a) Illustration on the role of nano-additive in improving atomization of the diesel + biodiesel fuel [Reprinted with permission from [85], Copyright (2020) Elsevier]. (b) The

picture showing the flame of nanofuel compared to that of B20 blend fuel [Reprinted with permission from [86], Copyright (2021) Elsevier]. (c) Achieving good mixing of the nanoparticles with the green fuel through sonication to ensure the necessary stability [Reprinted with permission from [85], Copyright (2020) Elsevier].

Out of many types of nanoparticles, Al_2O_3 nanoparticles have been favourably used in enhancing the properties of LCF and CNF. Such preference was ascribed to superior heat transfer rate and thermal conductivity of this nanoparticle [86-88]. Ansari et al. found that an Al_2O_3 -enabled green fuel (consists of 30% Jatropha biodiesel + 67% diesel + 50 ppm Al_2O_3 nanoparticles) exhibited an improved combustion properties owing to the good compatibility between the nanoparticles and the fuel, and the presence of oxygen in the Al_2O_3 nanoparticles [87]. The results were proven in where the brake-specific fuel consumption (BSFC) values of the biodiesel/diesel fuel was found to reduce upon blending with Al_2O_3 nanoparticles, implying better fuel efficiency (*i.e.*, lower fuel consumption for a given power output) was achieved. In addition, this nano-enabled green fuel attain combustion earlier and propagate more smoothly, resulting in a reduction in combustion noise from 91 dB (diesel fuel) to 88 dB (diesel fuel 70% + jatropha biodiesel 30%) and ~ 87 dB (diesel fuel 67% + jatropha biodiesel 30% + Al_2O_3 nanoparticles). In another study, Pourhoseini and Ghodrat noticed that the addition of Al_2O_3 nanoparticles to B20 fuel increases the intermediate soot particles (ISP) concentration; as shown in Figure 4b, the red tone color that belongs to the soot particles in Al_2O_3 -enabled B20 fuel flame picture is significantly higher than that of neat B20 flame [86]. Despite that, the NO_x emission from the combustion of Al_2O_3 -enabled B20 is slightly lower (~ 53 ppm) than neat B20 (~ 60 ppm) due to a reduction in the maximum flame temperature.

In terms of carbon-based nanoparticles, Bayindirli et al. successfully utilized the superior properties of reduced graphene oxide (rGO), which include excellent conductivity, good reactivity, and high specific surface area, to improve the combustion characteristics of biodiesel [80]. Results showed that the cetane number of the biodiesel increased from 55.3 to 57.1, and 57.9, upon added with 0 ppm, 50 ppm, and 75 ppm of rGO nanoparticles, respectively. At the same time, ignition delay time of the biodiesel was shortened upon the addition of rGO nanoparticles. The increase in cetane number and shortening of the ignition delay time optimize the process of achieving complete combustion. Important to note that graphene nanoparticles are known for their superior thermal conductivity (similar with Al_2O_3), it is therefore apparent that nanoparticles with good thermal conductivity are excellent candidates to enhance the functionality of LCF and CNF. They promote heat transfer between unburned fuel particles and the front flame, and can produce approximately twice the energy. This facilitates complete combustion, consequently reducing fuel consumption and the emission of harmful gases [80, 89]. It is worth noting that achieving good mixing of the nanoparticles with the green fuel is crucial, and it typically requires sonication to ensure the necessary stability. As shown in Figure 4c, a nanofuel remains stable after 12 hours upon subjected to 45 minutes of sonication.

Compared to green vehicle fuel, the available studies on nanoparticle-enabled SAF are scarce and in the early stages of investigation. Nevertheless, the role of nanoparticle-enabled LCFs and CNFs in advancing towards a low-carbon future is remarkable. While the addition of nanoparticles may not directly reduce the amount of CO_2 released during combustion, the nanoparticle-enabled LCFs or CNFs have been proven to exhibit complete combustion and other superior combustion properties compared to their neat counterparts. According to the field of Internal Combustion Engines (ICE), exploration for fuels that

support nearly complete combustion has been the core interest as it exclude the needs to perform changes in the design of the engine for using this fuel [80]. Hence, the improved combustion properties of nanoparticle-enabled LCFs or CNFs will enhance user confidence in choosing these green products to power their vehicles.

Table 4. Example of few recent works on nanoparticle-enabled LCFs and CNFs.

Fuel	Nanoparticle (size)	Concentration of nanoparticle	Remarks on changes in combustion properties of LCFs or CNFs.	Remarks on gaseous emission upon combustion LCFs or CNFs.	Ref.
30% Jatropha biodiesel+ 67% diesel	Al ₂ O ₃ (27 - 43 nm)	50 ppm	<p>The BSFC values reduced upon blending the biodiesel/diesel LCF with Al₂O₃ nanoparticles, implying better fuel efficiency (<i>i.e.</i>, lower fuel consumption for a given power output).</p> <p>At the brake power of 1.41 kW, the noise level at the front position was found to decrease from 91 dB to 88 dB and ~ 87 dB for diesel fuel, diesel fuel 70% + jatropha biodiesel 30%, and diesel fuel 67% + jatropha biodiesel 30% + Aluminium oxide 50 ppm, respectively.</p>	NA	[87]
Refined cottonseed oil-based biodiesel	rGO (NA)	50, 75 ppm	<p>The cetane number of the biodiesel increased from 55.3 to 57.1, and 57.9, upon added with 0 ppm, 50 ppm, and 75 ppm of rGO nanoparticles, respectively.</p> <p>At full load condition, the biodiesel blended with 50 ppm</p>	<p>The amount of CO emitted decline as the concentration of rGO used as additive in the biodiesel increases. Similarly, hydrocarbon emissions decrease with the increase in the additive concentration.</p> <p>Nevertheless, it was found that the NOx emissions rise by 9.70 % and</p>	[80]

			and 75 ppm of rGO nanoparticles exhibited ~ 9.63 °CA and ~ 9.54 °CA ignition delay time, as compared to ~ 10 °CA of neat biodiesel.	11.34 % for 50 ppm rGO-enabled biodiesel and 75 ppm rGO-enabled biodiesel, correspondingly, as compared to neat biodiesel.	
Hydrotreated vegetable oil (HVO)	Al (40 nm)	0.5 wt%	The HVO blended with 0.5 wt% of Al nanoparticles presented a higher burning rate and lower lifetime as compared to neat HVO.	NA	[90]
Palm oil-based Biodiesel (B20*)	Al ₂ O ₃ (22 nm)	300 – 500 ppm	Addition of Al ₂ O ₃ nanoparticles reduce the maximum flame temperature and relocate the peak temperature to the region upstream of the flame by enhancing the evaporation rate of the fuel droplets.	The CO emission from the Al ₂ O ₃ -enabled B20 is higher (~ 62 ppm) than neat B20 (~ 48 ppm) because the ISP burn in the flame reaction zone and are firstly converted to CO. However, the NO _x emission from the Al ₂ O ₃ -enabled B20 is slightly lower (~ 53 ppm) than neat B20 (~ 60 ppm).	[86]
Jatropha-based biodiesel (B20*)	Al ₂ O ₃ (51 nm) & CeO ₂ (32 nm)	30 ppm	At the full load, the Al ₂ O ₃ /CeO ₂ nanoparticle-enabled B20 biodiesel exhibited the lowest ignition delay (4.5 °CA) as compared to pure biodiesel (5.8 °CA), and pure diesel (7.5 °CA).	Upon blending with nanoparticles, the CO emission was reduced from 0.03 vol % to 0.02 vol %, NO emission was reduced from 1300 ppm to 978 ppm, and unburned hydrocarbon emission reduced from 13 ppm to 10 ppm.	[83]

			At the full load, the cylinder pressure of the Al ₂ O ₃ /CeO ₂ nanoparticle-enabled B20 biodiesel was 69.2 bar, lower than pure biodiesel (71.3 bar) and diesel (70.3 bar).	
Jatropha-based biodiesel (B100 ^{**})	Al ₂ O ₃ (51 nm) & CeO ₂ (32 nm)	30 ppm	At the full load, the Al ₂ O ₃ /CeO ₂ nanoparticles-enabled B100 biodiesel exhibited the low ignition delay (4.6 °CA). At the full load, the cylinder pressure of the Al ₂ O ₃ /CeO ₂ nanoparticle-enabled B20 biodiesel was 69.6 bar.	Upon blending with nanoparticles, the CO emission was reduced from 0.05 vol % to 0.02 vol %, NO emission was reduced from 1390 ppm to 1208 ppm, and unburned hydrocarbon emission reduced from 18 ppm to 12 ppm. [83]

*B20: 20 % biodiesel mix with 80 % diesel

**B100: 100 % biodiesel

NA: Information not available

2.4 As an Enhancer in Harvesting Low-Carbon Energy

In pursuit of the low carbon target, it is essential to gradually replace fossil fuels, which are the primary energy source that produce greenhouse gases, with more environmental friendly energy sources. Solar, geothermal, wind, hydropower, wave and tidal, biomass and biogas, and hydrogen energy are the sustainable energy supplies gaining much attention today. It is interesting to note that researchers have discovered numerous remarkable roles for nanoparticles in promoting the harvesting of the aforementioned sustainable energies.

2.4.1 Nanoparticles in Solar Energy

Nanoparticles have been widely used in the fabrication of solar cells, particularly to improve the sunlight absorption, enhance the light-to-energy conversion, and improve thermal storage and transport [91]. For instance, solar cells made of silicon nanoparticles possess an improved light trapping properties; the photocurrent can be enhanced up to ~ 10 % by stacking SiO₂ nanoparticles on top of the solar cell [92]. As compared to bulk silicon material, the nano-scaled silicon offers additional active sites for capturing photons from sunlight. In the quest for lightweight and flexible devices, thin film organic solar cells (OSCs) and perovskite solar cells (PSCs) have emerged as a potential replacement to the conventional inorganic silicon-based solar cells. In the development of thin film OSCs, ZnO nanoparticles [93-95], TiO₂ nanoparticles [96, 97], and CNTs [98, 99], quantum dots [100], and graphene nanosheets [101] are among the established electron transporting layers (ETLs). The ETL plays a crucial function in a solar cell as it collects and transfers electrons while inhibiting the recombination of holes [102, 103]. Similarly, highly efficient dye-sensitized

solar cells (DSSCs) can be customized by decorating its semiconducting photoanodes with nanoparticles [104, 105].

2.4.2 Nanoparticles in Geothermal Energy

Geothermal energy is a form of low-carbon energy that involves extracting heat from the Earth's core. Heat pumps and heat exchangers are the two important unit operations to harness this energy. To enhance the heat exchange efficiency, small quantities of nanoparticles are normally added as heat carrier to increase the optical properties, thermal conductivity, and convective heat transfer rate of the base fluid [106, 107]. One recent example is the adding of 0.1 % of Al_2O_3 nanoparticles to ethylene glycol/water base fluid; the resultant nanofluid showed an increase in ground heat exchanger performance of 19 % as compared to neat base fluid [108]. Research also found that the heat transfer enhancement increases linearly with the nanoparticle dosage. In this regard, Kaska et al. revealed, through simulation, that adding hybrid of aluminum nitride and Al_2O_3 nanoparticles in water (base fluid) resulted in an increase in heat transfer enhancement from 28% to 50% as the nanoparticle volume fraction was increased from 1% to 3% [109]. In addition to Al_2O_3 , other nanoparticles used in enhancing heat transfer rates are CuO, TiO_2 , Ag, CNTs, and etc [106, 110, 111]. Despite that, CNTs and graphene nanosheets have been used to reinforce high-density polyethylene (HDPE) for fabrication of ground heat exchanger pipes [112]; these two types of nanoparticles are known for their high mechanical strength.

2.4.3 Nanoparticles in Wind Energy

The usage of nanoparticles in wind energy harvesting is mainly on the building materials of wind turbines. Nanoparticles with high strength and lightweight properties (namely CNTs and graphene) can be used for wind turbines fabrication; This serves as an alternative to conventional wind turbines, which are typically large and heavy, posing challenges for transportation and installation [113]. An interesting work by Elhenawy et al. demonstrated that a vertical axis wind turbines (VAWT) built from kevlar-reinforced epoxy/functionalized-CNTs exhibits a reduction in maximum deflection to 14 %, and an increase in tensile strength by 19 % in the presence of 0.5 wt% functionalized-CNTs [114]. On the other hand, Dashtkar et al. modified polyurethane coating with graphene nanosheets for wind turbine blade leading edge protection; compared to neat polyurethane (5.81 kN/m), the polyurethane added with 0.5 wt% graphene nanoparticles was found to exhibit a higher tearing strength (8.45 kN/m). However, Boncel et al. concluded that while the nanoparticle-enabled wind turbine blades possess promising physicochemical and mechanical properties, this technology shall be put on industrial scale provided that reliability of bulk nanoparticle synthesis and economy feasibility can be answered [115].

2.4.4 Nanoparticles in Hydropower Energy

Similar to wind energy, the heart of the hydropower energy falls on the turbine in which rotation motion of the turbine blades is induced by water flow, leading to electricity generation. To protect the turbine from erosion, corrosion, and cavitation, coating layer containing both nano-scaled and micro-scaled tungsten carbide has been proven to give a lower porosity, better microstructure and hardness, and better slurry erosion resistance [116]. Meanwhile, the design of bearings, a crucial part of the hydraulic turbine, can be reinforced

by carbon-based nanoparticles (eg. nanodiamonds, CNTs, graphene) [117]. The nanoparticle-reinforced bearings showed an enhancement in both mechanical and tribological properties compared to polymeric materials.

Besides the conventional hydropower technology, two new and emerging technologies to harvest low-carbon energy from water resources are the reverse electrodialysis (RED) and the hydrovoltaic technology. The RED produces electricity by merging concentrated and diluted streams with differing salinity levels; research has showed that ion-exchange membranes, the key material of RED, can be modified with boron nitride nanotubes or MWCNTs for a better anti-fouling properties and energy generation performance [118-120]. On the other hand, the novel hydrovoltaic technology produces electricity via the nanoparticles-water interaction. The hydrovoltaic effects, which encompass drawing potential, streaming potential, waving potential, evaporation-induced electricity, and gradient-induced ion diffusion, are relevant to the application of nanoparticles [121-123]. For instance, drawing or dropping a water droplet on a graphene nanoparticle-based substrate give rise to a voltage of tens of millivolt (known as drawing potential); meanwhile, the evaporation-induced water flow within porous carbon materials can produce electricity of over 1 V [122]. Apparently, the use of CNTs represents a significant advancement, as these nanoparticles can expose all of their atoms on their surfaces, enabling substantial interaction with water molecules through electronic coupling, thereby promoting electricity generation [121, 124].

2.4.5 Nanoparticles in Wave and Tidal Energy

The incorporation of nanoparticles in both wave and tidal energy generation is less reported. The most relevant work was recently reported by a group of researchers from Mexico in which the team has developed a composite spray-coated with MWCNTs as the external layer of the tidal turbine blade; the MWCNTs formed electrical percolation network and provide a unique strain self-sensing properties [125]. The results demonstrated that the electrical resistance of the MWCNTs (in the tidal turbine blade) changes in accordance with the mechanical curve response, indicating its ability to self-sense strain.

2.4.6 Nanoparticles in Biomass and Biogas Energy

Biomass and biogas produced from plant sources are attractive low-carbon energies because they release fewer overall CO₂ emissions than coal burning [126, 127]. Nanoparticles are used to pre-treat the feedstock [128, 129] and to catalyse the production of both biomass and biogas [82]. In terms of catalysis, various nanoparticles have been proven to be effective heterogeneous catalysts to speed up a biofuel production rate. Gardy et al. synthesized a novel SO₄/Mg-Al-Fe₃O₄ nanocatalyst to catalyse transesterification of cooking oil and esterification of oleic acid [130]. The biodiesel yield was found to increase linearly with the increase of nanocatalyst dosage; meanwhile, results also showed that the nanocatalyst can be reused for five cycles with very minimal deactivation in the activity. Such a promising outcome can be ascribed to the strong acidity of this nanocatalyst, which was reported to be stronger than pure sulfuric acid. Another interesting feature of this nanocatalyst is its magnetic properties (provided by the Fe₃O₄ part) which enable the spent catalyst to be recollected using external magnetic field. Unlike the bulk catalysts, the tiny size of the nanocatalyst render to a lower mass transfer resistance and hence, shorten the reaction time

[131]. Other nanocatalysts proven to be effective in biofuel production are ZnO [132], MgO [133], CaO[134, 135], CNTs [132, 136], graphene [137], among others.

2.4.7 Nanoparticles in Hydrogen Energy

The production of H₂, one of the appealing low-carbon energies, can be driven using nanoparticle technology. For instance, the production of grey H₂ through steam methane reforming (SMR) was successfully catalysed by Ni–CeO₂/Al₂O₃ nanocomposites; a superior high catalytic efficiency, high stability over 8 hrs-operation period, and high H₂ yield were obtained in the presence of this novel nanocatalyst [138]. Noteworthy that production of H₂ through electrolysis has recently gained significant attention in the pursuit of green hydrogen. In this regard, a recent work by Wei et al. demonstrated that carbon black nanoparticles can increase the efficiency of hydrogen production by enhancing the H₂O electrolysis process [139]. In this study, carbon black nanoparticles were dispersed in water with the presence of sodium sulphate as the electrolyte; then, the hydrogen yield was traced using a Hoffman voltameter. A very positive result was observed whereby the H₂ production rate was successfully doubled from ~ 0.79 mL/min to ~ 1.66 mL/min in the presence of 0.1 wt% carbon black nanoparticles. The carbon black nanoparticles increased the electrical conductivity of the electrolyte which subsequently leading to higher yield of H₂.

In addition to H₂ production, nanoparticles also act as good sorbents to store the H₂ energy, given its high surface-to-volume ratio properties [140]. Solid-state nanoparticles (metal hydrides, carbon-based materials, and complex metal hydrides) have received remarkable investigation as prominent materials for H₂ storage [140-142]. Nano-scaled MgH₂ and LiBH₄ are two promising metal hydrides nanoparticles for this purpose [142, 143]. For

example, ball milling of MgH₂ and coconut shell charcoal (CSC) produced MgH₂/CSC of crystal size 23 nm; this nanoparticles could absorb 5.0 wt% H₂ in 5 min at 250 °C and 2 MPa H₂ pressure conditions [144]. On the other hand, 5.79 wt% H₂ absorption capacity was achieved in 5 min at 250 °C and 8 MPa H₂ pressure conditions using MgH₂ nanoparticles (15 – 20 nm)-decorated bamboo-shaped CNTs [145]. Further alteration of the nanoparticles with transition metals (e.g. Ti, Fe, Co, Ni, etc) and carbon materials (e.g. graphene, CNTs) improved the hydrogen storage properties and cycling property of the nanoparticles, respectively [146]. In conclusion, nanoparticles may answer to challenge pertinent to H₂ storage, which is one of the key bottlenecks of this low-carbon energy. Figure 5 summarizes the application of nanoparticles as enhancers in improving the harnessing of various low-carbon energies.

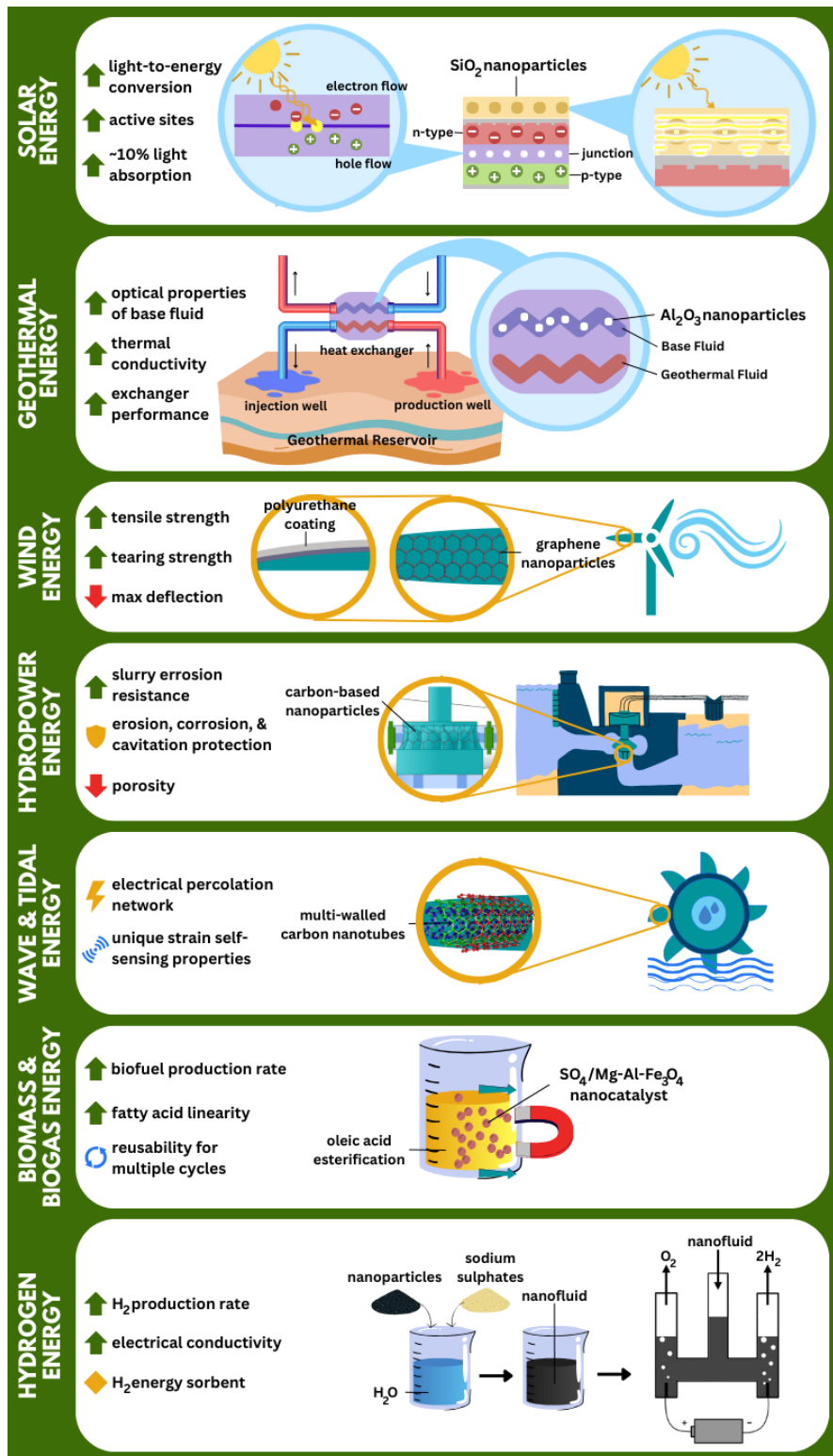
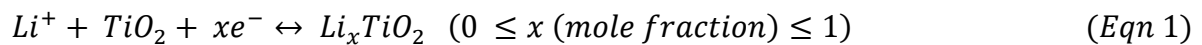
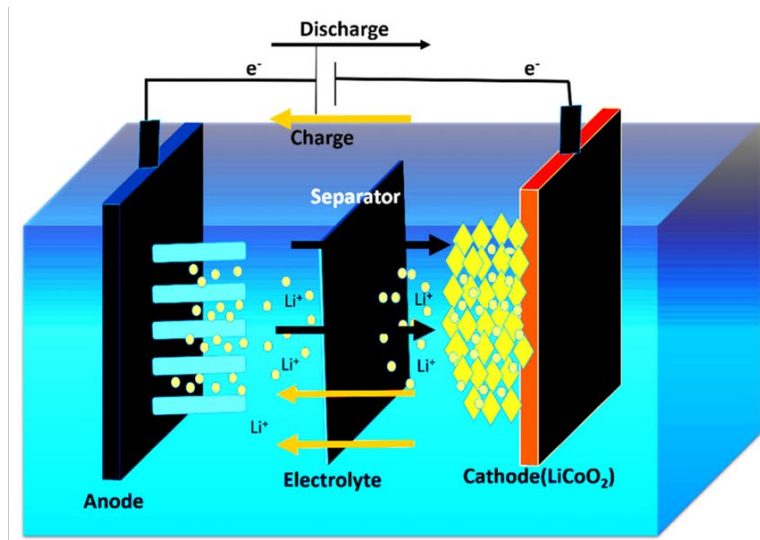


Figure 5. Schematic diagram illustrates the integration of nanoparticles to enhance various low-carbon energy harvesting technologies, enclosing solar energy, geothermal energy, wind energy, hydropower energy, wave & tidal energy, and hydrogen energy.

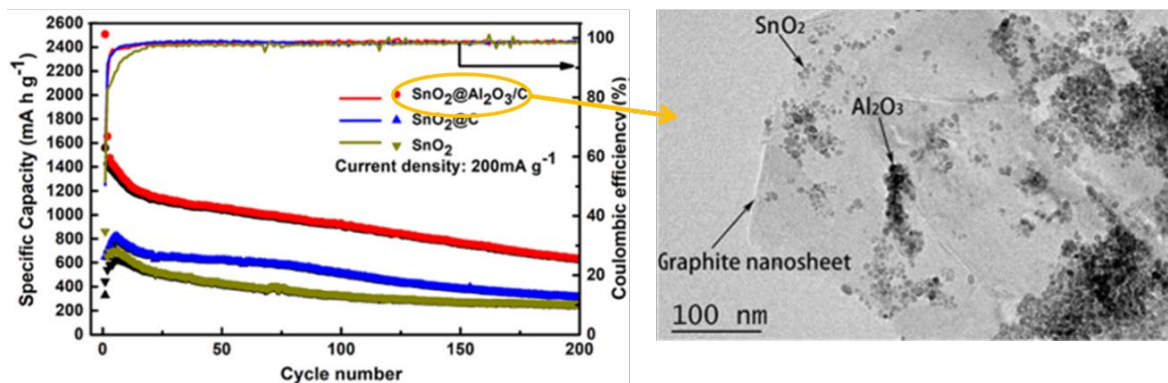
2.5 As Electrodes for Electric Vehicle (EVs) Batteries

Electric vehicles (EVs) have recently become the focal point of the low-carbon transportation industry [147, 148]. In particular, pure EVs release no CO₂ or other toxic emissions when driving, a condition known as zero tailpipe emissions. Owing to this, countries that are committed to net zero carbon emission aim (such as United Kingdom, Malaysia, Singapore, and China, among others) have gradually electrified their public transportation. However, the overall performance of the EVs is relying on their energy storage system (*i.e.*, battery) [149]; in this context, lithium-ion is the most common used battery for EVs [150-152]. A typical lithium-ion battery comprises of a cathode, an anode, and an electrolyte. During discharging, the Li⁺ ions produced from the anode will flow to the cathode; the opposite flow occurs during charging [153] (see Figure 6a). Such an insertion and removal of Li⁺ ions, following equation 1, are known as intercalation/de-intercalation.

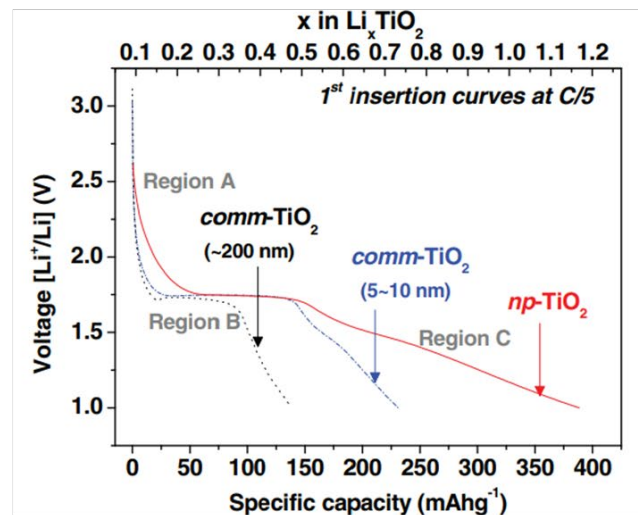




(a)



(b)



(c)

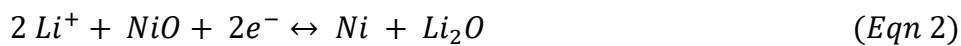
Figure 6. (a) Schematic diagram showing the working principle of a typical lithium-ion battery [Reprinted with permission from [153] under Creative Commons Attribution (CC BY)], (b) the cycle performance of battery at a current density of 200 mA/g using

SnO₂/Al₂O₃/graphene nanocomposites [Reprinted with permission from [154], Copyright (2020) Elsevier]. (c) The galvanostatic profile for the TiO₂ particles with size 200 nm and 5-10 nm [Reprinted with permission from [155], Copyright (2011) John Wiley and Sons].

Numerous research studies have proven the potential of improving the efficiency and life span of the lithium-ion battery through incorporation of nanoparticles. Nanoparticles can be incorporated into either anode or cathode of the lithium-ion battery. In this context, one of the frequently studied nanoparticles for this purpose is TiO₂ nanoparticles [153, 156]. As compared to the conventional graphite-based anode, the TiO₂ nanoparticles-based anode offer greater specific surface area to warrant more interfacial interaction between the electrode surface and the electrolyte, low volume fluctuation during the intercalation/de-intercalation of lithium ions, as well as greater conductivity that grant fast charging-discharging process [153, 157]. The polymorphs and size of nanoparticles also impact their ability to accommodate Li⁺ ions, thereby influencing the performance of the resulting battery [158]. In terms of polymorphs, the common studied TiO₂ polymorphs are anatase, rutile, brookite, and B (Bronze) [153]. The anatase TiO₂, which has an excellent theoretical capacity of 335 mAh/g and long-term cycling stability, is regarded as a more suitable anode material (as compared to graphite) for large-scale energy storage system [153, 159]. On the other hand, TiO₂-B, a monoclinic crystal structure, possesses a relatively lower density than the other three groups and is mentioned as another promising host for lithium intercalation due to simple lithium pathway [153, 158]. In terms of size, it has been reported that decreasing the size of the TiO₂ from 200 nm to < 10 nm improves the insertion of lithium ions owing to shorter diffusion path and higher interfacial area of the smaller counterpart (see Figure 6c) [155]. In a similar concept, research showed that the diffusion coefficients of lithium ions in nano-scaled

LiCoO₂ (a new cathode material) were more than 10 times higher than in micron-scaled LiCoO₂ [160].

Worth noting that, although TiO₂ nanoparticles have been rigorously studied in the fabrication of anode of lithium-ion batteries, it possesses a slightly lower theoretical capacity than the conventional graphite-based anode (372 mAh/g). In this regard, NiO nanoparticle stands out as a more prominent nanomaterial when a greater capacity is needed [161-163]. Research has found that a Ni-based anode exhibits twice the theoretical capacity (718 mAh/g) compared to the conventional graphite-based anode [162]. The conversion reaction between NiO and Li⁺ follow equation 2 [161, 164]:



In a study conducted by Wang et al. [165], a NiO nanocone array electrode was developed by electrodeposit Ni nanoparticles onto Ni foam followed by thermal oxidation. Promising results were obtained in where the NiO nanocone array electrode delivered a high reversible capacity of up to 1058 mAh/g, even after 100 cycles at 0.4 C. Such excellent performance was attributed to the good electrical contact. NiO is also favorable in anode fabrication due to its low cost, environmental friendliness, and wide availability [166]. Further doping of the NiO nanoparticles with metal can enhance its specific capacity through a synergistic effect [162]. For instance, doping NiO with metallic Ni forms Ni-NiO nanoparticles with better ionic conductivity; the metallic Ni also promotes the reverse reaction during charging [161].

Other than TiO₂ and NiO nanoparticles, Si nanoparticles [167, 168], Al₂O₃ nanoparticles [154], carbon-based nanoparticles [169], as well as various nano-scaled transition metal oxides [170] have emerged as potential anode candidate, as listed in Table 5.

In most cases, the nanoparticles, which are well distributed across the anode matrix, improve the structural integrity and conductivity, hence leading to stable reversible capacity over multiple charge-discharge cycles [171]. One-dimensional (1-D) nanoparticles (such as nanotubes, nanorods, nanofibers, and nanowires) may offer an additional advantage as they provide a rapid pathway for ion and electron transport [172]. Furthermore, the combination of two types of nanoparticles produced a composite with synergistic electrochemical activity which subsequently improved the cycle performance of the battery (see Figure 6b). The expansion of battery capacity and current density through the incorporation of nanoparticles shall increase public interest in supporting the usage of EVs for a low-carbon future.

Table 5. Summary of nanoparticles utilized to improve the characteristics of lithium-ion batteries.

Nanoparticles	Role in lithium-ion battery	Reversible specific capacity at (current density)	Cycle number tested in the study	Ref.
NiO nanocone array	Anode material	1058 mAh/g (0.4 C)	100 cycles	[165]
NiO nanoparticles	Anode material	~ 590 mAh/g (100 mA/g)	50 cycles	[173]
Ni/NiO nanocomposites	Anode material	635 mAh/g (2 C)	300 cycles	[161]
Carbon Dot-modified TiO ₂ @SiO ₂ nanocomposites	Anode material	299 mAh/g (100 mA/g)	100 cycles	[174]
(Ni,Co,Mn)Fe ₂ O _{4-x}	Anode material	650.5 mAh/g (2000 mA/g)	1200 cycles	[175]
Si@Al ₂ O ₃ @C nanocomposites	Anode material	1316.1 mAh/g (1000 mA/g)	100 cycles	[176]
FeNi ₂ S ₄ -rGO-MWCNTs	Anode material	77 mAh/g (50 mA/g)	60 cycles	[177]
Carbon-coated	Anode material	1946 mAh/g	100 cycles	[171]

Si/graphene/CNT		(100 mA/g)		
Si/C nanofiber/graphene nanocomposite	Anode material	964.68 mAh/g (100 mA/g)	100 cycles	[178]
SnO ₂ -Al ₂ O ₃ -graphite nanosheets	Anode material	495.7 mAh/g (1000 mA/g)	700 cycles	[154]
Si nanoparticles	Anode material	~ 1300 mAh/g (800 mA/g)	200 cycles	[179]
SnO ₂ -Co-carbon nanocomposite	Anode material	760 mAh/g (500 mA/g)	400 cycles	[180]
Al ₂ O ₃ /LiCoO ₂ nanocomposite	Cathode material	169 mAh/g (100 mA/g)	500 cycles (72 % retention)	[181]
MoO ₃ nanoparticles-coated LiNi _{0.5} Mn _{1.5} O ₄	Cathode material	109 mAh/g (10 C)	500 cycles (80.10 % retention at 1C)	[182]
LiMn ₂ O ₄ nanoparticles	Cathode material	138.12 mAh/g (0.1 C)	50 cycles (89.50 % retention at 1C)	[183]*
LiCoO ₂ nanoparticles derived from LiOR (R = Ph, ^t Bu, ⁱ Pr, Et, Me)	Cathode material	124 - 210 mAh/g (7.5 mA/g)	NA	[160]
LiCoO ₂ decorated with a nano-layer of carbon	Cathode material	123 mAh/g (1 C)	NA	[184]

*This study was to designed flexible lithium ion battery using nanoparticles

NA: Information not available

2.6 Nanoparticles in Decarbonisation of Crude Oil Extraction Industry

While the burning of fossil fuels is a main contributor to CO₂ emissions, the production of fossil fuels is still necessary in the transition period prior to full utilization of renewable energy. In this context, one of the on-going efforts paving the way towards a low-carbon future is to decarbonize the crude oil extraction process. The commonly used tertiary oil recovery (also known as enhanced oil recovery (EOR) [185]) methods, such as the in situ steam-assisted gravity drainage (SAGD) and the cyclic steam stimulation (CSS), are energy

and greenhouse gas emission-intensive [186, 187]. To cope with such limitations, new thermal, chemical, and gas-EOR methods improvised with nanoparticles have gained attention recently [188, 189].

Specifically, nanoparticles are small enough to penetrate into the reservoir and reach the pores where conventional injection fluids cannot [189], they transfer EOR chemicals deep into the reservoir [185], reduce viscosity and surface tension of the reservoir fluid [190, 191], alter wettability of the rock surface, as well as improve sweep efficiency [188, 192]. A study by Pandey et al. [193] showed that a chemical-EOR modified with MWCNTs reduced the interfacial tension by 56% and subsequently yielded a significant oil recovery factor of around 70% of the original oil in place (OOIP). Similarly, a recent work by Ahmadi et al. [188] demonstrated that SiO₂/KCl/xanthan nanocomposites can be used to improve the foamability and stability of sodium dodecyl sulfate (SDS) and cetyltrimethylammonium bromide (CTAB) surfactants. Important to note, this nanoparticle-modified foam was found to increase the oil recovery by 20% of the OOIP.

In addition to making the crude oil extraction process more effective, the nanoparticles-incorporated EOR method can assist in the reduction of carbon footprint [194]. Hashemi et al. [195] disclosed that a thermal injection oil recovery method, when augmented with nanoparticles, releases 50% less CO₂ than its non-nanoparticle counterpart. More interestingly, a new technique to inject nanoparticle-modified CO₂ foam into subsurface reservoirs can simultaneously increase oil recovery and sequester CO₂ [196, 197]. Apparently, there are many open opportunities to utilize nanoparticles to expedite the decarbonisation of the crude oil extraction industry.

3.0 Concluding Remarks and Prospects

In summary, the nanoparticle-enabled technologies to pave the way toward a low-carbon future have been in progress for decades and continue to advance rapidly. Thanks to their substantial specific surface area and unique properties (which are unattainable by their bulk counterparts) nanoparticles have advanced low-carbon technology in various forms: as sorbents for CCS applications, as catalysts to enhance the conversion and upcycle of CO₂ into value-added products (e.g., fuels, combustible compounds, and chemicals), as additives to boost the combustion properties of CNFs and CNFs, as enhancers to elevate low-carbon energy harvesting technology, as electrodes for low-carbon mobility batteries, and as additive in EOR applications. Nonetheless, the fundamental principle of low-carbon technology also hinges on the materials utilized, which should be produced or developed with minimal environmental impact. In this regard, there are on-going efforts to close the carbon cycle in this area of research specifically to reduce the carbon footprint during the manufacturing/synthesis of nanoparticle. Here, the available and prospect area for future research include: (i) developing industrial-scale green synthesis of nanoparticles using plant-based extracts, (ii) upcycling CO₂ by transforming it into carbon-based nanoparticles (such as carbon nanotubes, calcium carbonate nanoparticles, and graphene) through mineralization and consumption processes, (iii) achieving low carbon manufacturing especially with regard to the energy-intensive top-down nanoparticle synthesis approach, (iv) integrating advanced processing technology (eg. microwave, ultrasound) to shorten the heating time or reaction time during bottom-up synthesizing of nanoparticle, and (v) performing a detail life cycle assessment to evaluate the carbon footprint of the nanoparticle synthesis process. Important to note that nanotechnology is no longer in its infant phase of development. Henceforth, it is anticipated that the utilization of nanoparticles in low-carbon technologies may complete the

syndication stage and diffusion stage in the near future, while more innovation in nanoparticle-enabled low-carbon technologies continues to be explored.

Credit Authorship Contribution Statement

Swee Pin Yeap: Conceptualization, Visualization, Resources, Writing – Original Draft. Kah

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Declaration of Competing Interest

The authors declare no competing financial interest.

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