1

Sustainability Issues in the Twenty-First Century and Introduction to Sustainable Ways for Utilization of Natural Resources

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CONTENTS

1.1 Introduction ............................................................................................................................ 1
  1.1.1 Utilization of Conventional Resources Adopting Cleaner Routes ........................... 3
  1.1.2 Utilization of Renewable Biological Resources ..................................................... 5
  1.1.3 Utilization of Unconventional Resources ................................................................. 9
  1.1.4 Optimization of Resource Utilization ................................................................. 11
  1.1.5 Sustainability Assessment ...................................................................................... 12
  1.1.6 Conclusion ................................................................................................................ 14

References .................................................................................................................................... 14

1.1 Introduction

In the twenty-first century, the world is facing many social, environmental, and economic challenges of the time, but the greatest challenge remains to keep this planet in a better shape for future generations. To achieve this goal, the concept of sustainability is evolved, which emphasizes the overall development of a sustainable society. The following paragraphs outline the chronological evolution of the terms “sustainability” and “sustainable development” (Web 1).

The name sustainability is derived from the Latin sustinere (tenere, “to hold”; sus, “up”). “Sustain” can mean “maintain,” “support,” or “endure” (Stivers 1976; Meadows et al. 2004). The history of sustainability can describe human-dominated ecological systems from the earliest civilizations to the present time (Barbier 1987). It is reported that the concepts of sustainable development and sustainability were used in the past (~twelfth to sixteenth centuries) in forest management as “sustained yield,” which is the translated form of German term Nachhaltiger Ertrag (Grober 2007; Ehnert 2009). However, over the past five decades, the concept has been significantly broadened (Ehnert 2009).

In the seventh decade of the twentieth century (the 1970s), the term sustainability was used to describe an economy in equilibrium with basic ecological support systems. In its classic report on the “Limits to Growth,” the Club of Rome used the term “sustainable” for the first time in 1972, which has later been highlighted by scientists in many fields (Grober 2007; Finn 2009). To address the concerns over the impacts of expanding human development on the planet, economists have also presented an alternative term “steady-state economy.”
Since the 1980s, sustainability has been used more in the sense of human sustainability on the planet earth. In 1980, sustainable development was first referred to as a global priority in “The World Conservation Strategy” published by the International Union for the Conservation of Nature (IUCN 1980). To guide and judge the human conduct affecting nature, five principles of conservation were raised by the United Nations World Charter for Nature in 1982 (UNWC 1982). The report “Our Common Future” also commonly known as “Brundtland Report” was released by the United Nations World Commission on Environment and Development in 1987. In this report, sustainability is defined as a part of the concept of sustainable development that ensures the needs of the present without compromising the ability of future generations to meet their own needs (Brundtland 1987; Smith and Rees 1998). The Concept of Sustainable Economic Development was also published in 1987 by the economist Edward Barbier, in which he had advocated that the goals of environmental conservation and economic development are not conflicting and can reinforce each other (Barbier 2006).

In 1992, the UN Conference on Environment and Development (UNCED) published the “Earth Charter,” also known as the “Rio Summit,” “Rio Conference,” or “Earth Summit” (Portuguese: ECO92), which outlines the building of a sustainable peaceful global society in the twenty-first century. The action plan 21 Agenda identified information, integration, and participation as key building blocks to help countries achieve sustainable development (UNCSD 2012). To strengthen the implementation of sustainable growth, the UN Conference on Sustainable Development 2012 (UNCSD 2012), also known as Rio 2012, Rio+20, or Earth Summit 2012, was held in Brazil in 2012. After a debate on more than 90 environmental issues initially proposed, the United Nations Environment Programme (UNEP) also promulgated 21 emerging issues for the twenty-first century in 2012 (UNCSD 2012; UNEP 2012). In 2013, four interconnected domains, namely, ecology, economics, politics, and culture, were identified for reporting sustainability (Magee et al. 2013), which is related to our long-term cultural, economic, and environmental health as well as vitality. Sustainability can be achieved by linking these issues together rather than considering them as separate. An economically and environmentally viable process may not be sustainable until it is socially desirable as shown in Figure 1.1 (Smith and Rees 1998).

FIGURE 1.1
Venn diagram of sustainable development at the confluence of three constituent parts. (https://en.wikipedia.org/wiki/Sustainability.)
Sustainable development is a dynamic process or an action plan or a road map for a desirable future state for human societies in which living conditions and resource use continue to meet human needs without undermining the “integrity, stability, and beauty” of natural biotic systems (Web 1). It also ensures the carrying capacity of natural systems with the social, political, and economic stability (Stivers 1976). Hence, devising methods and mechanisms for utilization of natural resources for sustainable development of a human society is the primary goal of sustainability. A sustainable society focuses on the minimum use of nonrenewable resources such as minerals and fossil fuels; conservation of finite stocks of biodiversity; the maximum use of renewable resources such as freshwater, soils, and forests; and conservation of absorptive capacity of local and global sinks of wastes such as air and water resources. It also provides an opportunity for each human being to develop itself in freedom, within a well-balanced society, and in harmony with its surroundings. Thus, some important approaches for achieving sustainability can be lesser consumption of natural resources such as water and energy; reduction of energy wastage; more use of fuel efficient engines in vehicles and machines; more recycling and reusing of waste materials; and more efforts for protection of soil and forests.

This chapter mainly focuses on various sustainable ways of utilizing natural resources, which may be either exhaustible or renewable. The former includes minerals, coals, petroleum, nuclear, and natural gas, whereas the latter includes a variety of sources grown in or obtained from land, ocean, and air. Some examples of such renewable resources are biomass, water, wind, solar, microorganisms, herbs, and plants. Many of these resources are being utilized conventionally (without taking sufficient measures for the environmental, social, cultural, and health needs). These resources can be utilized in a more optimal and eco-friendly way to ensure sustainability. Further, some resources are not yet well exploited, although these have good potential for contribution toward sustainability. The following sections describe how sustainability can be achieved through various ways of utilization of natural resources. This chapter is organized as follows: Section 1.1.1 describes utilization of conventional resources via cleaner routes, Section 1.1.2 highlights exploitation of renewable biological resources, Section 1.1.3 explains utilization of unconventional resources, Section 1.1.4 illustrates methods of optimization of resource utilization, and Section 1.1.5 emphasizes sustainability assessment.

1.1.1 Utilization of Conventional Resources Adopting Cleaner Routes

Energy is one of the most significant inputs for economic growth and human development, and coal has been recognized as the most important source of energy. Today approximately 40% of the world’s energy requirement can be achieved through coal. However, the major constraint in the utilization of coal is that ~65% of its global reserves contain low-rank coal, which on combustion produces serious ecological and environmental threats due to emission of obnoxious greenhouse gases. Extraction of coal from mines and its processing for application in power plant also add different types of pollutants in air and water. For the sustainable utilization of coal, emphasis is being laid on the development of suitable coal extraction technologies as well as energy recovery from the existing coal resources using clean coal technologies. Various clean coal technologies include coal beneficiation with ultrasound enhanced technology; coal gasification—both conventional and molten and plasma gasification; co-combustion with gasification; carbon capture and sequestration (CCS) using precombustion, postcombustion, and oxy-fuel combustion techniques; and clean combustion techniques including technologies for NOx reduction, high-temperature air combustion, chemical looping combustion, and chemical looping reforming. Unconventional coal
technologies such as underground coal gasification (UCG) and coal to liquid oil (CTL) production are also two important clean coal technologies. Integration of a mixture of these clean coal technologies in existing power generating systems is necessary to achieve a minimal energy penalty for CCS. According the National Energy Technology Laboratory, Morgantown, West Virginia, deployment of new advanced technologies can reduce emission as well as coal consumption for the production of a certain amount of electricity by increasing the overall plant efficiency (Web 2).

It has also been predicted that using clean power plants, the greenhouse gas emissions can be reduced by \(~30\%\) by 2030 with reference to the emission in the year 2005 (Web 3).

Petroleum crude oil, which produces useful products such as liquefied petroleum gas, naphtha, gasoline, kerosene, jet fuel, diesel, heating oil, and asphalt base, is another major source of energy after coal. The above products are produced from crude oil through atmospheric and vacuum distillation processes. Various conversion processes such as cracking and hydrotreating are also used to alter product distribution. A good amount of residue is also generated after vacuum distillation of crude oil called as vacuum residue (VR). The amount and quality of VR are dependent on the metal and sulfur content of crude oil as well as its viscosity. Utilization or disposal of this residue is a great concern of a refinery as it influences the economy and environmental requirements. Due to gradually degraded quality of crude oil, it is becoming heavier day by day, resulting in more residues related to more contaminants. Thus, upgrading of heavy residues is becoming a priority area for the sustainability of petroleum refinery. A number of approaches (both hydrogen addition and carbon rejection) are developed for upgrading the heavy residues. Some of these processes are cracking, hydrocracking, visbreaking, delayed coking, solvent deasphalting, and gasification (Ancheyta and Rana 2004; Speight 2013). Recently, nanotechnology and biological routes have also been investigated to explore the upgrading of heavy residue.

Natural gas is widely used as fossil fuel next to coal and petroleum crude. It mainly contains methane along with some higher hydrocarbons and CO₂. It is used for power and heat application in power plants as well as in the transportation sector as compressed natural gas. It can also be used to produce hydrogen through steam reforming. Hydrogen produced from natural gas can further be used to produce electricity in a fuel cell, or it can be used for the synthesis of many chemicals such as ammonia. Application of natural gas in a Honda Civic can reduce global warming pollution by \(~15\%\) than a conventional gasoline-powered Civic. However, \(~30\%\) emission reduction is possible if a gasoline–electric Civic hybrid is used in place of a conventional gasoline-powered Civic. Further, the conversion of natural gas to electricity or hydrogen and its subsequent application in plug-in vehicles or fuel cell vehicles can give \(~40\%\) saving of global warming emissions (Web 4 and Web 5).

Therefore, hydrogen production from natural gas is more sustainable than its other utilization routes. Conventional steam reforming units have very large capacity and hence are more economical. Recently, extensive research has been conducted to increase the efficiency of the small-scale reforming process using compact reactors such as micro-channel reactors and monolith reactors.

Another nonconventional fossil fuel, which has attracted great attention in recent years, is oil sand, which is basically a mixture of clay, sand, water, and bitumen (a dense and extremely viscous form of petroleum). Oil sand deposits have been found in many countries around the world, including Canada (~169 billion barrels), the United States (~28 billion barrels), Venezuela (~100 billion barrels), Russia (~60 billion barrels), and some other countries (Web 6). However, the largest deposit of oil sands is found in Canada. More than 320 billion cubic meters (two trillion barrels) of global oil sand deposits has been estimated. Efforts are made around the world to extract and produce usable oil from oil
sands, and the Athabasca deposit in Alberta is utilizing the most available technologically advanced production process. It is predicted that the oil sand production in Canada would increase 1.7 times by 2024 with respect to the production in the year 2014 (from 2.3 million barrels per day to 4 million barrels per day) (Web 5). Many international companies such as Shell, ExxonMobil, Sinopec, BP, Total, Chevron, and PetroChina are set to expand their oil extraction from oil sands in the upcoming years. However, developments of more cost-effective and eco-friendly methods are required for the utilization of this resource.

1.1.2 Utilization of Renewable Biological Resources

The major breakthrough in energy security can be established if renewable resources are utilized properly. Among the renewable resources, some are biological resources comprising mainly land biomass and biomass from marine and aquatic sources, whereas wind, ocean, hydro, and solar sources are some other important nonbiological sources of renewable energy. Microorganisms in wastes can also be used for energy production.

Biomass can be converted into liquid biofuels, which can be used in transportation. The major biofuel is bioethanol, which has high octane number and other desirable fuel properties. It is also environmentally friendly. It is mainly produced from abundant renewable biomass through a biochemical route in which low-cost and plentiful biomass from nonfood sources is first broken down into a number of sugars through pretreatment and chemical or enzymatic hydrolysis. This is then followed by fermentation in the presence of biocatalysts such as yeast, to produce bioethanol. Any sugary substances (derived from cane and beet), starchy agricultural crops, crop residues, lignocellulosic biomass, and algal biomass have the potential to be a feedstock for bioethanol production. The pretreatment steps become more important for handling lignocellulosic biomass. Many kinds of microbes such as *Saccharomyces cerevisiae*, *Zymomonas mobilis*, thermophilic *Thermobacter ethanolicus* or thermophilic ethanologen, thermophilic anaerobic bacteria, *Clostridium thermocellum*, *Thermoanaerobactenum saccharolyticum*, aerobic mesophilic fungus, *Trichoderma reesei*, fungal glucoamylase, cellulase-producing fungus *Aspergillus niger*, and thermotolerant yeast *Kluyveromyces* sp. IIE453 are used for bioethanol production (MTCC 5314) (Ray et al. 2013).

Production of bioethanol from edible biomass is under debate as the requirement of food crops is increasing due to increased population. Thus, application of lignocellulosic biomass for bioethanol production is a very important area for sustainable production of bioethanol. However, this process is not well established for commercial scale production due to low biodegradability of lignocellulosic biomass and complexity in product separation steps. Systematic efforts are required to develop a new technology to produce ethanol from lignocellulosic biomass. Currently, lignocellulosic ethanol can be competitive with fossil fuels at a crude price of $100 per barrel or more. However, in 2030 it is expected to be competitive at a crude price of $75 per barrel (Clixoo 2016). A combined technology based on the integrated biorefinery concept (BioGasol) for production of biogas, hydrogen, methane, ethanol, and solid fuel (lignin) from biomass must be employed to get sustainable low-cost production of lignocellulosic bioethanol (Ahring and Langvad 2008). The possibility of producing longer chain alcohol such as butanol, isopropanol, and 2,3-butanediol from lignocellulosic biomass should also be explored.

The energy density of bioethanol is ~40% less than that of regular gasoline, whereas for biobutanol, it is ~10% less than that of regular gasoline, which shows that biobutanol has more energy density than bioethanol. Physicochemical properties of these two alcohols, responsible for blending and antiknocking properties are also comparative (Mužíková et al. 2014). Thus, biobutanol can be more suitably used as gasoline blend than
bioethanol. It has been attracting strong attention in recent years (Jang et al. 2012). The yield and speed of production of biobutanol is dependent on the types of microorganisms and substrates used. Higher alcohol concentration (>3%) shows toxic effects to microorganisms (Qureshi and Maddox 1995). To overcome this limitation, new microbes are used and genetic modification of microbes is made (Durre 2007) to get high alcohol concentration withstanding strains. The mutant strains of *Clostridium acetobutylicum* and *C. beijerinckii* have been used to produce high concentrations of cellulosic n-butanol. Efforts are made to develop this process in commercial scale (Huang et al. 2010).

Among the nonconventional and renewable biosources, algal biomass seems to be the most promising one as its growth rate is very high. Through photosynthesis, algae produce carbohydrates, part of which is converted into lipid and protein through different metabolic pathways. The carbohydrate can form ethanol through fermentation, whereas lipid/oil can produce biodiesel through transesterification or other route. The proteins can be recovered and used for many applications. Algal biofuels such as bioethanol and biodiesel are highly biodegradable, are nontoxic, and contain no sulfur. Algae also help to reduce greenhouse gas by consuming CO$_2$. Figure 1.2 shows the necessary processing steps for production of various kinds of biofuels including bioethanol from algae.

Apart from bioethanol and biodiesel, biomethane, biohydrogen, electricity, and syngas can also be generated from algae. However, each fuel production requires a number of unit operations with different complexities. The major processing steps include pretreatment, conversion, final product separation, and purification. Pretreatment processes include oil extraction or thermochemical steps to produce algal oil or bio-oil along with the residues. The conversion steps consist of transesterification (biodiesel), hydroprocessing (green diesel, green jet fuel, and green gasoline), biochemical conversion (oxygenates-bioethanol, biobutanol, biomethane), and thermochemical gasification (syngas).

Biomass of plants and algae is proven as a competitive feedstock for energy production. These renewable resources can also be converted into biofertilizer, which has a significant potential for the improvement of soil properties for better crops. Although green revolution has improved the food security in the world by applying chemical fertilizer...
Sustainability Issues in the Twenty-First Century

and pesticides, it has significantly affected the soil conditions and the crop yield is under threat in the twenty-first century. Further, it has also induced many contaminations in soil as well as groundwater. Use of biofertilizer and biopesticides can help to restore the soil properties and reduce pollution. Biofertilizers are generally produced from renewable resources, which utilize living microorganisms. These fertilizers when applied to seed, plant surfaces, or soil promote the plant growth by digesting large biopolymers such as proteins, carbohydrates, fibers, and fats, which increase the availability of primary nutrients to the host plant. Natural nitrogen fixation as well as phosphorus and potassium solubilization processes are promoted by living microorganisms to add nutrients (growth-promoting substances—amino acids, sugars, and fatty acids) to the soil. The main sources of biofertilizers are bacteria, fungi, and cyanobacteria (blue-green algae) and other natural plant resources such as neem. Some examples of living microorganisms for biofertilizers are Rhizobium azospirillum, Azotobacter, and Acetobacter. Biofertilizers can accelerate soil fertility, promote plant growth, reduce the use of chemical fertilizer, scavenge phosphates from soil layers, and increase the availability of nutrients. There are numerous uses of biofertilizers such as production of legumes, paddy crops including rice, wheat, corn, mustard, cotton, potato, and many other vegetables. Farm yard manure (a type of biofertilizer) can be produced by using raw materials such as cow dung, cow urine, and waste straw and dairy wastes after producing gobar gas through composting. Like biofertilizers, the biopesticides, which control pests, suppress the growth of other bacteria, fungi, and protozoa, are also derived from plants, bacteria, animals, and some minerals. Some examples of biopesticides are fermented curd water, cow urine extract, chilli–garlic extract, neem cow urine extract, baking soda, and canola oil. Trichoderma viride can act as a biofungicide. These biofertilizers and biopesticides are very effective in providing long-term benefits compared to chemical pesticides and other chemical products.

Like land biomass, renewable marine biomass has also high potential to support the sustainability of the society. The ocean represents a rich source for pharmaceutical products, nutritional supplements, cosmetics, agrichemicals, and enzymes (Vignesh et al. 2011). It can also provide many natural products having a unique structure, which can be used as a source of bioactive compounds suitable for combating deadly diseases such as cancer, osteoporosis, acquired immunodeficiency syndrome (AIDS), human immunodeficiency virus (HIV), Alzheimer’s disease, and arthritis. Many compounds possessing analgesic, anti-infective, antimicrobial, antitumor, and anti-inflammatory properties have also been developed. Marine microorganisms, algae, and invertebrates are primarily found to be the source of such lifesaving compounds (Jha and Zi-rong 2004; Bhadury et al. 2006). The first marine-derived cancer drug Cytosar-U® (Medicines By Design 2011) is produced decades ago from a Caribbean Sea sponge, which is used to treat leukemia and lymphoma. Yondelis is another marine-derived cancer drug, which is isolated from Ecteinascidia turbinata and is under clinical testing (Bhadury et al. 2006). A growing number of marine fungi are the sources of novel and potentially lifesaving bioactive secondary metabolites. A nerve toxin Prialt™ Dublin, Ireland has been derived from cone snail and is being marketed by Elan Corporation, plc, in Dublin, Ireland. This drug jams up nerve transmission in the spinal cord and blocks certain pain signals from reaching the brain. The production of medicines from indigenous marine-pharmaceutical biomass with competitive price may stimulate new markets for the agriculture sector and can also create many job opportunities (Bruckner 2002).

Biomass from hills also possesses high potential for maintaining sustainability in the twenty-first century. The Himalaya regions in India have traditional knowledge of ayurvedic/herbal medicine. Some rare and endemic species of medicinal and aromatic plants are available in this region along with many other species, which are valuable to the
Sustainable Utilization of Natural Resources

pharmaceutical and cosmetic industries (Banerji and Basu 2011). Approximately 45% plants including 8000 species of angiosperms, 44 species of gymnosperm, 600 species of pteridophytes, 1736 species of bryophytes, 1159 species of lichens, and 6900 species of fungi have medicinal properties (Samant et al. 1998). In 2008, the size of the global market of herbal drug was ~US$60 billion per annum (Sharma et al. 2008). The demand of herbal drugs is also increasing very fast and its global market size in 2017 may reach ~US$ 100 billion per annum (Sharma et al. 2008). Thus, the Himalayan medicine system, a vast treasure of herbal medicine, should be exhaustively explored and used for the economic regeneration of the local people as well as for the medical benefit of the whole world.

Based on chemical investigations on the herbs of traditional tribal folk available in the herb layer of the Himalayas for medicinal use, it has been established that a number of modern lifesaving drugs are the prominent constituents of these herbs. A number of lifesaving drugs such as reserpine, pilocarpine, ephedrine, theophylline, vincamine, atropine, aconite, and colchicines have been derived from traditional folk medicinal herbs. The following plants are the main constituents of the herb layer of the Great Himalayas: Carex nubigena, C. muricata, Ainsliaea aptera, Viola canescens, Goldfusia dalhosiana, Stellaria monosperma, Bupleurum lanceolatum, Valeriana jatamansi, Scutellaria angulosa, Justicia simplicex, Oxalis corniculata, Rubia cordifolia, Anaphalis contorta, Anemone rivularis, Swertia spp., Eupatorium spp., and Dipterocarpus spp. Herbal drugs are used for the treatment of cancer, AIDS, malaria, liver diseases, kala-azar and other infectious diseases, hypertension, antiarthritic, bronchial asthma, and so on. These have also the antitumor, hepatoprotective, and ant fibrotic activities. These can also act as anti-inflammatory, sex hormone and oral contraceptive, an antidote to insect bites and snakebites, febrifuge, a stimulant to uterine contraction, and a sedative (Goswami et al. 2002).

Taxol obtained from yew tree, a rare Himalayan plant, is used for chemotherapy for cancer, breast, and ovarian cancer. The cost of this medicine is US$13 per milligram with a market potential of US$870 million. Ashwagandha (Withania somnifera) is also used for cancer treatment. Merremia peltata and Malpighia emarginata, flavonoids of Plantago asiatica L., have been employed for AIDS/HIV inhibitors. There are noticeable advantages for herbal medicines compared to synthetic ones, and research is being conducted to further explore the herbal sources for medicinal use.

Not only the higher plants and herbs but also microorganisms have the potential to help sustainability in the twenty-first century. Microbial fuel cells (MFCs) provide new opportunities for the sustainable production of energy from biodegradable, reduced compounds and effluents (Rabaey and Verstraete 2005). They convert biochemical metabolic energy into electrical energy. Thus, they can also be used simultaneously for wastewater treatment and electricity (Das and Mangwani 2010). Most recent developments in MFC technology include its use as microbial electrolysis cells, in which anoxic cathode is used with increased external potential at the cathode and hydrogen is produced. Phototropic MFCs and solar-powered MFC technology for electricity generation are also few latest developments. MFCs have the following operational and functional advantages over the technologies currently used for generating energy from organic matter (Rabaey and Verstraete 2005).

1. Substrate conversion efficiency is high.
2. They can operate efficiently at ambient and even at low temperatures.
3. They do not require gas treatment.
4. They do not need energy input for aeration when the cathode is passively aerated (Rabaey and Verstraete 2005).
5. They can be used in locations lacking electrical infrastructures.
The MFC technology is evaluated relative to current alternatives for energy generation. Though it is renewable, eco-friendly, sustainable, and useful for wastewater treatment, electricity generation, and bioremediation of toxic compounds at the same time, commercial exploitation is still awaited. Studies on economic feasibility for large-scale production are needed.

1.1.3 Utilization of Unconventional Resources

With the rapid depletion of fossil fuel reserves and the ever-increasing demand of energy with the associated cost of energy, it is an imperative necessity to explore unconventional renewable energy resources in the developing countries such as India. The major types of unconventional renewable energy sources include solar, wind, mini and micro hydroenergy, geothermal energy, wave energy, tidal power plants, and ocean thermal energy conversion; all of these have the potential to meet future energy needs. Among these resources, solar and wind energy are considered as the most important in India. Although solar energy production has some drawbacks such as low-energy density per unit area and uncertainty of availability with extreme seasonal variation, extensive efforts are made around the world to develop this technology as it is nonexhaustible and completely pollution free. Solar energy seems very promising for countries such as India, Pakistan, and China, as these fall in the solar zone (Enerco 2015). Presently, around 13.5% of the total energy production in India takes place through renewable routes and the solar energy contributes approximately 10% of the renewable energy production. It is also growing very fast with a highly ambitious target to produce 100 GW (100,000 MW) by 2022 (Chaurey and Kandpal 2010).

There are principally two methods of solar energy utilization: the thermal conversion of solar energy for heating applications and the photovoltaic (PV) conversion of solar energy into electric power generation. Solar heaters or thermosyphon solar collectors are used to raise the temperature of the fluid (water or air) flowing through the collector. However, poor heat transfer coefficient of air flowing through the collector results in low thermal efficiency (Saini and Saini 2005). Solar thermal systems also require a storage. In PV conversion, direct electricity is produced by means of silicon wafer PV cells called solar cells. It is easy to install and seems a better option for power generation if the life cycle energy use and greenhouse gas emission are considered, although large-scale exploitation of PV may lead to some undesirable environmental impacts in terms of material availability and waste disposal. Further, the cost and maintenance of solar cells are the greatest problems (Kellogg et al. 1998; Celik 2003; Arun et al. 2007; Hrayshat 2009; Singh et al. 2009; Bekele and Palm 2010).

Combustion of fossil fuels emits high amount of CO$_2$ in the atmosphere, and globally around 30 Gt CO$_2$ has been emitted in a year in recent times. The CO$_2$ concentration in the atmosphere has increased from 300 ppm in preindustrial time to 400 ppm in the twenty-first century due to the emissions from fossil fuel combustion. Further, it is expected that in the next few decades also, fossil fuels will be the main source of energy; thus, it may be difficult to reach the target of CO$_2$ emission reduction even though the energy efficiency is improved and renewable energy is used. Therefore, efforts are made to capture CO$_2$ at its source of production as well as its utilization for the production of value-added products. Various technologies have been developed in recent years to capture CO$_2$ and its storage effectively and economically, although these are not matured yet for postcombustion power plants. The captured CO$_2$ can be used as a solvent or a working fluid, a storage medium for renewable energy as well as a feedstock for various chemicals. It can also be used for
Sustainable Utilization of Natural Resources

the growth of microalgae. It is a well-known fact that CO₂ helps the growth of autotrophic biomass through photosynthesis. Thus, properly designed method for the utilization of CO₂ can be applied for the growth of microalgae and other biomass for energy feedstock. Different energy storage chemicals, such as syngas, methane, ethylene, formic acid, methanol, and dimethyl ether, can be produced from CO₂. Various polymeric materials can also be produced by inserting CO₂ into epoxides. Approximately 0.3–0.7 Gt/year of CO₂ may be consumed through various chemical conversion pathways (Web 7). Conversion of CO₂ into inorganic minerals through electrochemical reactions followed by the necessary mineralization reaction has been a strong interest in recent years as these can be used in building materials. A preliminary estimate suggests that ~1.6 Gt/year CO₂ could be consumed if 10% of the world’s building materials were replaced by such a source. Enhanced oil recovery, which can increase oil recovery by 10%–20%, is another important commercial technology for CO₂ and its storage. Similarly, methane recovery from unmined coal seams can also be done using CO₂.

Water, which is abundantly available in nature, can be a source of energy. In hydroelectric power plant, the kinetic energy of water is used to produce electricity; the water molecules are also used for the production of hydrogen through steam reforming, gasification, and so on. Hydrogen is also produced from water through other routes such as electrolysis and photocatalytic reactions. Hydrogen production from water through electrolysis is an old concept; however, it suffers with high capital and maintenance costs of the process (NREL 2009). A large number of investigations are being conducted to reduce the cost of this process so that water can be used more environmentally friendly for energy/hydrogen production.

Freshwater is a finite and vulnerable resource and essential to sustain life, development, and the environment. In a broader sense, water is linked up with all kinds of resources, namely, energy, agriculture, finance, industry, tourism, environment, and fisheries. A systematic process called integrated water resources management (IWRM) is evolved for the allocation and monitoring of water resources and their use in the context of economic, social, and environmental objectives to achieve sustainable development. IWRM considers interdependency among all the different uses of finite water resources. The final statement of the ministers at the International Conference on Water and the Environment in 1992 (so called the Dublin Principles) recommended the development of IWRM to promote essential changes in practices for improved water resources management (Web 8; Young et al. 2008). IWRM is hence a process, which promotes the coordinated development and management of water, land, and related resources in order to maximize economic and social welfare in an equitable manner without compromising the sustainability of vital ecosystems. The concept of IWRM is a way forward for the sustainable development and management of the world’s limited water resources.

Different techniques, systems, or models such as geographic information system, database, and integrated water resources planning model are used for IWRM. Each model is complex in nature and needs a sophisticated software to solve. For example, time-series water balance model comprises water demand forecasting module, water balance module, water quality module, water allocation/costing module, resource management/development option module, and development scenario evaluation module. Similarly, watershed modeling is another interactive modeling employed for IWRM which consists of several components. Modeling through advanced techniques is being applied to achieve reliable water security, enhanced agricultural yield, improved living standard, and sustainable land-use and community consensus. However, because IWRM practices depend on the context, sometimes it becomes challenging to translate the agreed principles into concrete action.
1.1.4 Optimization of Resource Utilization

Optimum use of resources is another important approach for sustainable development. It improves the economy of a process as well as preserves resources for further application. In the process industry, the optimization of water and energy usage is an interesting area, which has a significant impact on the overall economy of the process. To maintain sustainability, reduction in water consumption as well as wastewater discharge is essential. Regeneration and recycling of wastewater in the process can reduce freshwater requirement while satisfying environmental regulations. Water minimization in the process industry (both freshwater and wastewater) can be made through improved operations and equipment as well as by eliminating or reducing water-intensive practices. Changes in heating and cooling methodologies, prevention of leakage from water-carrying systems and water spillover also help to reduce water consumption. Effective water monitoring and maintenance program is thus necessary. Optimization strategy is important in achieving not only freshwater minimization and minimum wastewater generation but also a subsequent reduction in the cost of operation. Integrated process design or process synthesis called pinch technology is one of such approaches based on recycle and reuse practices. The branch-and-bound method of optimization is also frequently employed to design the flow sheeting in chemical process engineering. To simultaneously target the minimum freshwater requirement, minimum wastewater generation, maximum water reuse, and minimum effluent treatment, a novel limiting composite curve also called as a source composite curve was proposed (Bandyopadhyay and Cormos 2008). To address the water management issues of the integrated process involving regeneration and recycle through a single treatment unit (single component), graphical representations as well as analytical algorithms can be used. In multicontaminant problems, the proposed methodology can be applied based on the limiting contaminant. Efforts are made to develop a general approach for dealing with multicomponent problems.

Chemical process industries such as sugar and paper, distillery are generally energy intensive. The energy costs in these industries are on the order of 25%–30% of the total cost of manufacture. Therefore, energy conservation in these industries is necessary, which can be achieved by reducing energy losses in the process. The issue of energy conservation is interrelated with steam generation, process steam demand, condensate extraction and blow-off, incorporation of other heat economy measures in the plant, proper choice of all equipment with conceptual optimal design features, design alternation of existing equipment and network, and so on. Efficient evaporator system design with vapor recompression and bleeding of vapors as well as splitting of multiple effect evaporator setups improve the energy economy. Improved heat exchanger network can also reduce energy consumption. Thus, energy optimization policies should be employed to evaluate the energy consumption in a specific industry, mainly steam usage, and then various modeling techniques should be utilized to optimize the energy consumption. Statistical multiple linear or nonlinear regression models have been used to study the effects of variables on the steam consumption (Raghavendra and Arivalagan 1993). Pinch technology has been used to optimize the heat exchanger network to reduce energy consumption. It also helps to achieve a targeted energy scenario with improved network.

Like process industries, water and energy optimization can be achieved in domestic and commercial complexes through implementing the concept of green building, which refers to a structure, and using a process that is environmentally responsible and resource
Sustainable Utilization of Natural Resources

efficient throughout a building’s life cycle. The whole process consisting of design, construction, operation, maintenance, renovation, and demolition requires the cooperation of the design team, architects, engineers, and clients. The main goals of a green building are better sustainability index, sitting and structure design efficiency, energy efficiency, water efficiency, materials efficiency, indoor environmental quality, reduced wastes, and maintenance cost. The benefits of green buildings are evaluated based on environmental, economic, and human aspects, including thermal comfort, indoor environmental quality, health, and productivity (Hauge et al. 2011). Some important green building assessment tools are as follows: Leadership in Energy and Environmental Design, Building Research Establishment Environmental Assessment Method, Green Building Council of Australia, and Green Star (Zuo and Zhao 2014).

1.1.5 Sustainability Assessment

With increasing awareness on sustainability issue in the twenty-first century, extensive research is being conducted around the world to introduce new technologies/products, with less environmental impact, high economic benefit, and acceptable social impact as sustainability is related with these three major factors. Thus, to ascertain the sustainable development, it is imperative to quantify the sustainability aspect of a process/product before taking any decision on it by the policy maker. Many indicators have been developed for this quantification purpose, and some frameworks have been devised by many organizations. For example, sustainability metrics covering economic, environment, and social dimensions and involving a different set of indicators have been formulated by the Institution of Chemical Engineers (IChemE) (Labuschagne et al. 2005). The metrics as shown in Figure 1.3 was initiated to assess the sustainability performance of the process industry.

To assess the environmental impacts associated with all the stages of a product/process, the life cycle assessment (LCA) is used. The role of LCA is crucial in determining the values of various metrics and emissions along the entire chain of a product. These values are further used to overcome sustainability challenges through creative thinking, and the whole process is called sustainability life cycle assessment (SLCA). The SLCA is nothing

![FIGURE 1.3]

but an assessment tool and an accompanying process to get a strategic overview of the full scope of social and ecological sustainability at the product level. An effective life cycle approach can identify where potential trade-offs may occur across different media and across the life cycle stages (Fava et al. 1993).

Considering the scarcity and degraded quality of fossil fuels, biofuels are attracting high attention as a renewable fuel. Extensive research is being carried out around the world to improve the quality and yield of biofuels from different biomass feedstocks. Although apparently it seems that biofuels are more attractive than fossil fuels, the strategies for sustainability have to be thoroughly assessed at several levels such as relevance of biofuels with respect to sustainable development, sustainable transport, main sustainable transport strategies, technology strategies, alternative fuel strategy, biofuel strategy from the first- to the fourth-generation biofuels, sustainability frameworks, standards, criteria and certification, theoretical perspectives, and methodology in respect of transfer effects, industrial ecology, and life cycle assessment to assess their suitability as transport fuels (Holden and Gilpin 2013). To be more specific, to assess the sustainability of biofuels for road transport, one should consider the key characteristics of biofuels as well as some essential criteria as stated below before adopting assessment policies (Curran 2013):

1. The four main dimensions for sustainable development must be satisfied if a biofuel is used.
2. Gains from biofuel strategies must be competitive to gains from other sustainable transport strategies, such as reducing transport volume and altering transport patterns.
3. Gains from using one generation of biofuels (e.g., first generation) must be compared favorably to gains from using other generations of biofuels (e.g., second through fourth generations).
4. Benefits from using biofueled vehicles must be competitive with those from using other alternative-fueled vehicles.

It is noteworthy to mention that no single strategy such as increasing the use of biofuels, reducing traffic volumes, improving public transport, increasing the use of plug-in hybrids, and long-range-battery electric vehicles can achieve sustainable transport; a full portfolio of strategies is required in this regard (Wang et al. 2009).

Further, because the potential feedstocks for biofuels are large in number and with different characteristics, it is challenging for the current LCA approach to apply a distributed decision-making methodology due to the vast scope of information needed to address so many alternatives (Halog and Bortsie-Aryee 2013). Thus, multicriteria decision analysis, such as the analytic hierarchy process, is used to determine the most critical criteria, variables, and indicators to stakeholders, which can represent their conflicting interests with respect to economic, environmental, technological, and social dimensions of systems sustainability (Holden and Gilpin 2013).

It is forecasted that biofuels will contribute 6% of the total fuel use by 2030 (Hannon et al. 2010), and algal biomass is emerging as a promising feedstock for biofuel production due to its high growth rate; however, a number of hurdles should be overcome by this technology to be competitive in the fuel market (Hannon et al. 2010; Sander and Murthy 2010). Some important challenges are identification of suitable strains and their improvement in terms of both oil productivity and crop protection, allocation and use of nutrient and
resource as well as production of co-products to improve the economics of the entire system. Investigation is being conducted around the world on the LCA for algae biomass utilization with an aim to provide baseline information for the algae biodiesel process (Sander and Murthy 2010). Like road transport biofuels such as bioethanol and biodiesel, the biomass-derived jet fuel (biojet fuel) is also becoming a key renewable fuel in the aviation industry’s strategy. The biojet fuel has the potential to reduce operating costs, environmental impacts, and greenhouse gas emissions. Additionally, it must meet the American Society for Testing and Materials (ASTM) International specifications and potentially be a 100% drop-in replacement for current petroleum jet fuel. Such fuels can be produced through alcohol-to-jet, oil-to-jet, syngas-to-jet, and sugar-to-jet pathways. The main challenges for each technology pathway include conceptual process design, process economics, and LCA.

1.1.6 Conclusion

In this chapter, the sustainability issues in the twenty-first century along with various approaches for achieving sustainability and its assessment have been presented. The historical evolution of the term “sustainable development” in relation to sustainability has been briefly discussed. Attention has also been paid to the relation among environmental conservation, economic development, and population growth, which are in fact not conflicting and can reinforce each other with the interaction of four terms—economics, ecology, politics, and culture. The existing technology, research trend, improvement in processing, and future prospects regarding sustainability through utilization of conventional resources adopting cleaner routes have been addressed. The specific examples of clean coal technologies, downstream processing of heavier petroleum fractions, and hydrogen from natural gas and liquid fuel from oil sands are cited. Sustainability through utilization of renewable biological resources such as ethanol and butanol from lignocellulosic biomass, oil from algae, utilization of biofertilizer and biopesticides, exploring lifesaving drugs from marine sources as well as from Himalayan herbs, and bioenergy production through MFCs have been discussed. A critical analysis on sustainability through utilization of unconventional resources, specifically, utilization of solar energy production and PV cells, CO₂ for fuels and chemicals, hydrogen from water, and integrated water management, has been included. Sustainability through optimization of resource utilization such as water and energy optimization in process industries as well as green buildings has been assessed. Finally, life cycle analysis as the sustainability assessment, multicriteria decision tool for road transport biofuels, algal biofuel with special emphasis on residual biomass processing, and sustainable production and utilization technologies of biojet fuel have been highlighted.

References


