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Role of Chemistry in Sustainable Development

R. M. G. Rajapakse

Department of Chemistry, University of Peradeniya, Peradeniya 20400

Chemist plays a pivotal role in sustainable development. American Chemical Society identified seven sustainable development goals and additional five of them that a chemist has direct contributions. In this feature article, chemistry and sustainable development are defined at the inception. The article then describes how a chemist is contributing to achieve seven sustainable development goals. Wherever possible, examples are taken from locally achieved developments. Let us work for national and global development through achieving the needs of the present generation without compromising the ability of future generations to meet their own needs.

INTRODUCTION

The Oxford dictionary defines chemistry as "the branch of science concerned with the substances of which matter is composed, the investigation of their properties and reactions, and the use of such reactions to form new substances" [1]. Indeed, this is the branch of science that deals with matter. In general, matter involves all physical substances that occupies space and possesses rest mass, especially as distinct from energy. However, chemistry also deals with energy transformations involved in chemical processes as exemplified in chemical thermodynamics and statistical mechanics. Matter that a chemist is dealing with may be from atoms, molecules and ions to planets, stars, galaxies. Nonetheless, a chemist should be conversant in analyzing matters of all size scales from picometers to lightyears. Chemist discovers complicated structures of matter, their stereochemistry, chemical and physical properties, and chemical reactions, and uses this knowledge to design and develop new substances that are beneficial to the humankind, other animals, ecosystem, and so forth. The substance, material, device, and product that a chemist develops should meet the criteria of sustainable development or else the invention is detrimental. The Brundtland Report, published in October 1987, by the United Nations, through the Oxford University Press, defines sustainable development as the "development that meets the needs of the present generation without compromising the ability of future generations to meet their own needs" [2–4]. That is the development preserving environment and ecosystem without exhaustion of raw materials. This means that the sustainable development should correlate with the organizing principle for meeting human development goals without undermining the integrity and stability of the natural system. The Rio Process initiated at the 1992 Earth Summit in Rio de Janeiro first institutionalized the sustainable development. The United Nations General Assembly, in 2015, adopted seventeen sustainable development goals (SDGs) addressing the global challenges, including poverty, inequality, climate change, environmental degradation, peace, and justice [4]. Chemistry plays an essential and mandatory role in helping society achieve the SDGs. The American Chemical Society (ACS) identified seven priority SDGs and five additional SDGs that are foundational to the work of the chemistry community [5]. Chemistry is central in developing technologies for addressing key issues such as zero hunger, human health and well-being, clean water and sanitation, affordable and clean energy, industries, innovation & infrastructure, responsible consumption & production, and climate action.

CHEMISTRY IN SUSTAINABLE DEVELOPMENT GOALS

Sustainable Development Goal 2: Zero Hunger

Food is essential for living of humans and animals. The development of Harbor-Bosch process that converts nitrogen in air to ammonia, conversion of phosphate minerals to soluble phosphorus species, and extraction of potassium from minerals made it possible to develop synthetic fertilizers to produce sufficient food for ever increasing global population. Advances in chemical research will enable the development of better protection of plants and crops from pest infestations, improve food production and transportation channels, extend the shelf-life of postharvest products and food items through improved packaging, and maintain food quality and safety. Development of high-yield seeds and improved fertilization methods will undoubtedly increase the food production while reducing soil erosion. Fortification of foods to supply essential nutrients can combat malnutrition issues. Better utilization of fertilizers will enable the prevention of eutrophication due to excess N- and P- leached into water reservoirs. N-fertilizers such as urea and ammonium compounds are highly water soluble and a significant proportion leach into water bodies thus losing the fertilizers and creating adverse effects. Incorporation of these soluble fertilizers in suitable carriers for developing slow- and constant-release formulations over a period eliminates the problem of wastage and its consequent adverse effects. It is a task of chemist to develop such technologies to help farmers to better use fertilizers without wasting. On the contrary, phosphate fertilizers are not very water soluble and making them water soluble by developing charged nanoparticles of phosphates for allowing plants to readily absorb them is also a task of a chemist. This will eliminate washaway of phosphate fertilizers eventually causing eutrophication. Climate change caused by environmental pollution is a serious global problem that results in lengthy droughts and flooding. Long-lasting droughts create water shortages which can adversely affect vegetations. Therefore, developing technologies for water retention in plants will help retard this problem. The Cutler group at University of California, Riverside, developed quinabactin which is a compound that mimics the plant hormone abscisic acid (ABA) that helps to retain water in some plants [6–8]. However, they found that this compound does not work for some key crops such as wheat and tomato. Extensive structural studies performed to find out reasons for this effect revealed that ABA binds to ABA receptors present in plants through two positions but in some ABA receptors quinabactin binds to only one position. Having realized the problem, the research team developed a new compound called opabactin that binds to ABA receptors in two positions of all ABA receptors. Therefore, the latter compound works better than the former in helping to retain water in many crops [9]. Figure 1(a) shows the chemical structures of quinabactin and opabactin and 1(b) reproduced with permission shows the structure-guided optimization and thermodynamic profiling of abscisic acid receptor agonists that led to the discovery of opabactin.

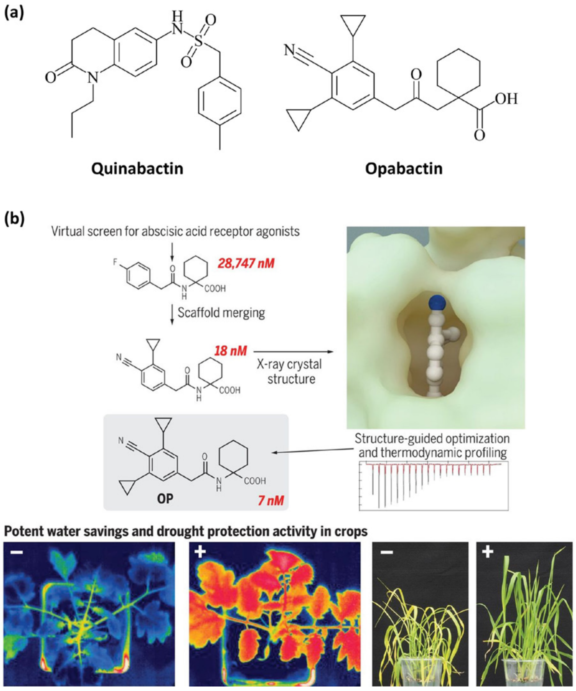

Figure 1: (a) Chemical structures of quinabactin and opabactin. (b) Structure-guided optimization and thermodynamic profiling of optabactin as a potent water saving compound for drought protection of crops (Reproduced with permission from [9]).

Phosphate recovery from sludges such as sewage is yet another important area for manufacturing P-fertilizers. While there are several methods available to do so, microbial fuel cell-based bio-electrochemical wet phosphate recovery from iron phosphate sewage sludge presents a low-cost and scalable process as reported by Blatter et al [10]. The process flow diagram reproduced with permission is given in Figure 2. Here, they used iron salts to competitively precipitate phosphate in a microbial fuel cell. We have also used various nanomaterials to recover phosphate present in wastewaters, their adsorption isotherms, kinetics of adsorption, revealed [11,12]. There are many other reports for the recovery of phosphate from various waterbodies [13–18].

Managing pests and diseases without having to use toxic chemical pesticides is also an area where chemist can contribute. The sustainable crop protection involves several methods. Out of these, the use of natural pesticides to combat pest and disease issues is an interesting area where less harmful natural materials are used instead of synthetic pesticides. Spraying mild soap or oil can be used to destroy sap-sucker insects. Urine diluted with water kills some pests. Boiled tobacco leaves also used to protect crops from pest attacks [19]. Pyrethrins are natural pesticides extracted from flowers of some plants. In general, pyrathrins have lower toxicity to humans and mammals. Pyrethrin insecticides extracted from Tanacetum cinerariifolium provide a human-safe and ecologically friendly alternative to widely used synthetic insecticides. However, care should be taken to ensure not to expose to high doses since even the natural pesticides at high doses are toxic.

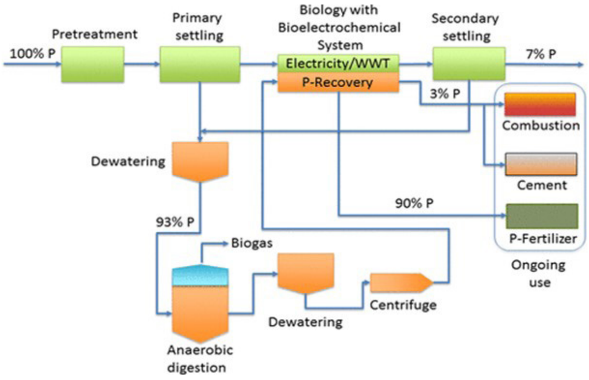

Figure 2: The process flow diagram for phosphate recovery from sewage. Reproduced with permission from [20])

Food protection and spoilage detection are another important aspect in combatting hunger. Ma et al. developed a highly sensitive, printable nanostructured conductive polymer wireless sensor for food spoilage detection [21]. They developed a nanostructured conductive polymer-based gas sensor with high sensitivity of $\Delta R/R0$ = 225% toward 5 ppm ammonia NH3 and unprecedented sensitivities of 46% and 17% toward 5 ppm putrescine and cadaverine, respectively, with the near-field communication (NFC) labeling technology using smartphones with non-line-of-sight sensing functions to improve the environment, human health, and quality of life. Increasing shelf-life of food products is done through active packaging. This involves modified atmosphere packaging (MAP) where manipulated compositions of carbon dioxide, oxygen and nitrogen are used to preserve appearance, texture, taste, freshness, and hygiene while extending the shelf-life and quality of the food [22]. Since the MAP has a higher level of CO_2 and lower levels of O_2 than those present in the outside air, the respiration, biomass loss and microbial spoilage are reduced. Additionally, SO_2, CO and ethanol are used in limited quantities. For foods that are packaged for use in a relatively long term, the passive modified atmosphere packaging can be used. Here, the properties of the food product and the permeability of the packaging material are used to achieve and maintain the desired atmosphere. The respiration of fresh food produces CO_2 to maintain a high level of concentration. In the active MAP, a vacuum is created first and then required quantities of desired gases are introduced. Use of desiccants to remove excess water vapour, hygroscopic pads or sheets to remove moisture, deliquescent salts, such as calcium chloride and magnesium chloride packed in sachets are also used in dry food packaging. Also, silica gel, modified starch, natural clay, calcium oxide, and calcium chloride are some moisture absorbers used. Oxygen scavengers are used to control oxidation of food products, rancidity of fats and oils, ripening and senescence of fresh produce, staling of bakery products, and controlling aerobic bacteria that would damage food products. Ethylene absorbers are used to remove phytohormones to delay ripening of fruits and some vegetables. The oxygen scavengers such as potassium permanganate, activated carbon and finely dispersed mesoporous silica are used in the form of film and sachets.

Sustainable Development Goal 3: Good Health & Well-Being

Advances in chemistry enabled understanding how human health is implicated by diseases and hazardous chemicals present in environmental segments such as air and water and discovering new medicines to combat diseases and removing environmental pollutants. Chemistry is central in developing tools for disease diagnosis and control. Green chemistry approaches should be used in all these chemical processes such as manufacturing of pharmaceuticals, development of disease diagnosis methods, and so on. The old practice of using harmful solvents should be minimized and biomimetic routes or harmless solvents such as supercritical carbon dioxide are encouraged. The American Chemical Society (ACS) has a Green Chemistry Institute (GCI) and its Green Chemistry Roundtable is dedicated to the implementation of green chemistry in pharmaceutical and other industries. In collaboration with relevant industries, the ACS-GCI developed a variety of high-quality tools and metrics to help scientists and engineers to make better decisions about chemical selection and route and process design incorporating green chemistry approaches [23] . They found that the chemical selection (*i.e.*, solvents, reagents, etc.) has a decisive role in determining synthetic process cost and environmental, safety and health impacts across the life cycle. The use of high-pressure liquid chromatography (HPLC), ultra-high pressure liquid chromatography (UHPLC), and advancing supercritical fluid chromatography (SCFC) to UHP-SCFC enabled faster and more efficient separations. They have also developed an Analytical Method Greenness Score (AMGS) Calculator to provide a straightforward metric to enable the comparison of separation methods used in drug development. The AMGS metric includes the solvent health, safety and environmental impact, cumulative energy demand, instrument energy usage, and method solvent waste to benchmark and compare one method to another. The ACS-GCI member companies are also provided with biocatalysts guide to replace synthetic catalysts with enzymes. The green chemistry and also enables the reduction of waste in the industrial processes. To this effect, we developed a low-cost, low-temperature route to breaking ilmenite structure and separating titanium and iron components for the synthesis of phase-specific titanium dioxide, iron oxide and zero-valent iron nanomaterials. The waste contains only sodium chloride that can also be recovered in a saltern ultimately discharging clean water to the environment [24–28]. We have also improved industrial wastewater treatment technologies by introducing precipitation of heavy metals and zinc as their sulphides at the beginning and introducing Fenton and photo-Fenton processes for oxidative degradation of organic contaminants and finally both aerobic and anaerobic bacteria based microbial treatment plants to remove soap molecules and ions. The microbial plant sludge generated was analyzed for its zinc, aluminium and heavy metal contents and methods were developed to remove them well below the maximum allowable levels stipulated by the Central Environmental Authority of Sri Lanka. The nutrient value of the toxic substance removed bacterial sludge was determined and C:N ratio, NPK and micronutrient contents were analyzed. Table 1 shows the data obtained. The high N content was reduced by diluting the sludge with other raw materials and organic fertilizer formulations were produced.

Table 1: Selected tolerance limits for the discharge of industrial wastewater to different categories under the act of Central Environmental Authority (1534/18). Reproduced from AAS Mendis, Ph.D. Thesis, University of Peradeniya, 2021.

Characteristics	**Value**	**Requirement (SLS 1236:2003) guidelines**	**Method of test**
pH	6.5 – 7.5	6.5 – 8.5	ISO 10390
Organic carbon, % by mass	37.20	20	2.2.1.2 Method
Nitrogen content, % by mass	6.20	1.0	2.2.1.1 Method
Phosphorous content, as P_2O_5 % by mass	3.5	0.5	SLS 645: Part 5
Potassium content, as K_2O % by mass	0.1	1.0	SLS 645: Part 4
Magnesium content, as MgO % by mass	0.08	0.5	SLS 645: Part 6 Section 1
Calcium content, as CaO % by mass	7.1	0.7	SLS 645: Part 6
C/N ratio	6/1	20/1	

The organic fertilizer thus produced were analyzed for its nutrient value and impurities and having confirmed that they are in accordance with the recommended values, the fertilizer was applied to vegetable and fruit plantations. The soil, plant parts, fruits and vegetables were analyzed as a function of repeated application for heavy metals, zinc and aluminium and made sure that they are within the maximum allowable limits [29]. We are currently working on developing bacteria and fungi-based potassium releasing system from feldspar.

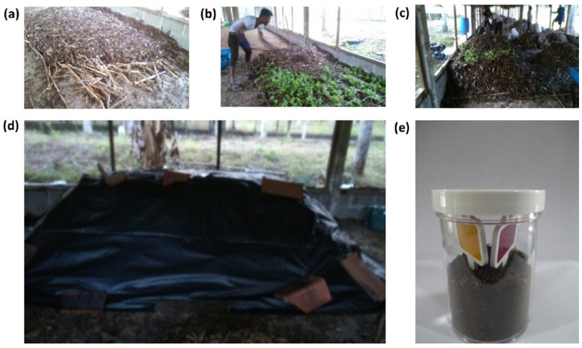

Figure 3: Stages of organic fertilizer production (a to d) and maturity testing (e). Reproduced from AAS Mendis, Ph.D. Thesis, University of Peradeniya, 2021.

Sustainable Development Goal 6: Clean Water & Sanitation

Access to clean drinking water is a fundamental right of a human and chemist plays an important role in providing clean drinking water. Chemist helps to develop clean water resources by removing water pollutants and also desalination processes. Current research also involves the development of low-energy, high-efficiency separation methods for removal of metal ions and micropollutants. Also, chemist develops strategies for reduced water usage in industries and reduced wastewater production. As explained earlier, it is the responsibility of the chemist to develop technologies for industrial wastewater treatment plants and to make sure the water that is finally discharged to the environment is safe and pollutant free. There are two aspects that needs consideration here: solar assisted desalination and heavy metal removal. The solar assisted desalination is a way of producing clean water in a greener manner by using electricity produced from solar energy. The Elemental Water Source™ is a plug & play is the first of such industry that utilizes 100% solar energy produced from off-grid solar panels for desalination process making it economical and environmentally friendly.

Metal-organic frameworks can be used to remove heavy metals, such as Pb^{2+} and Hg^{2+}, selectively and rapidly from water [30]. Also, we developed several nanomaterials that can remove heavy metals [31–34].

Sustainable Development Goal 7: Affordable & Clean Energy

Chemist plays a major role in developing Earth-abundant, non-toxic materials for use in solar cells, fuel cells, supercapacitors and batteries, thermal energy collection and in wind energy conversion. Also, new catalysts are developed to improve efficiency of chemical industrial processes, and to optimize process design. Additionally, chemist works on replacing expensive Nobel metal catalysts by low-cost materials such as clay-polymer nanocomposites as oxygen reduction cathodes in fuel cells to replace platinum [34-36], graphite, expanded graphite and graphene products as counter electrodes in solar cells [37-40], and in converting quartz to solar grade silicon for solar cell production [41]. Figure 4 (a) shows large electrodes fabricated from Sri Lankan vein graphite in developing 10 kW h Zn/Br_2 flow battery and (b) shows a lab-scale version of the flow battery.

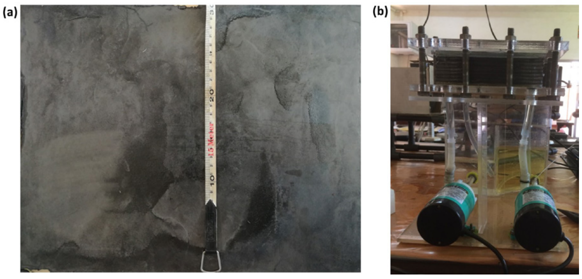

Figure 4: (a) Graphite electrodes fabricated for developing 10 kW h Zn/Br_2 flow battery. (b) A lab-scale version of a Zn/Br_2 flow battery.

Nanowires for electrochemical energy storage by Zhou et al. reviews the state-of-the-art research progress on nanowires for electrochemical energy storage, from rational design and synthesis, in situ structural characterizations, to several important applications in energy storage including lithium-ion batteries, lithium-sulfur batteries, sodium-ion batteries, and supercapacitors [35]. The cleanest fuel is hydrogen because the combustion of hydrogen gas produces water as the only product that is environmentally benign. However, hydrogen as $H_2(g)$ does not exist as it can escape out atmosphere. It exists mainly as water and hydrocarbons. Currently, $H_2(g)$ is produced in the process of hydrocarbon cracking in the petroleum industry. However, there are two reasons as to why this process is not attractive: rapid depletion of fossil fuel deposits and environmentally unfriendly processes used. Other alternative is to split water to $H_2(g)$ and $O_2(g)$ electrochemically or photo-electrochemically through the efficiencies of these processes are significantly low and currently used technologies demand expensive platinum as the catalyst. Chemists have developed relatively inexpensive transition metal-based catalysts, such as oxides, sulfides, hydroxides of cobalt, nickel, iron etc. However, unlike platinum, most of these inexpensive catalysts can accelerate either hydrogen evolution reaction (HER) or oxygen evolution reaction (OER) but not both. To overcome this difficulty, chemists developed a novel heterostructured catalyst consisting of hollow cobalt sulfide (CoSx) and nickel-iron (NiFe) layered double hydroxide (LDH) nanosheets that simultaneously boosts both the half-reactions [36]. Figure 5 shows an AC Transit hydrogen fuel cell bus. Credit: Eric Fischer [37] .

Figure 5: An AC Transit hydrogen fuel cell bus. Credit: Eric Fischer [37]

Sustainable Development Goal 9: Industries, Innovation & Infrastructure

Chemist plays at least three major roles in this goal: (i) upgrading infrastructure and retrofit production facilities of chemical processing industries to become more sustainable, (ii) making the infrastructure more sustainable and resilient by the design, synthesize and manufacture of innovative advanced materials and coatings and (iii) encouraging chemistry research that enhances innovation for commercial applications. In this sense, we collaborate with ten Sri Lankan industries: namely, ATG Lank Ltd., Teejay Lanka Ltd., Bogla Graphite Pvt. Ltd., LTL Galvanizers Pvt. Ltd., Isabella and Sarasavi Industries, Sarasavi Exports Pvt. Ltd., Varna, and Sithra Industries, CODEGEN International Pvt. Ltd. where we develop highly value-added products. The sustainability in this goal involves assessing greenness of a reaction or product and developing greener analytical techniques, developing biobased chemicals, homogeneous and heterogeneous catalysts based on organic, organometallic, inorganic and biological materials, managing the extraction, use, reuse of depleting materials, developing tools and metrics to measure greenness, controlling process engineering, rational molecular design for reduced toxicity, environmentally friendly solvents and solvent-free synthesis methods, and converting waste to chemicals. It is noteworthy to mention here that waste is just the important materials in a wrong place at wrong times. There is nothing called waste and recycling waste to valuable materials is an important step forward in sustainable development. Figure (6) shows collaboration with industries (a) ATG Lanka Ltd., (b) Teejay Lanka Ltd., and (c) LTL Galvanizers Pvt. Ltd. The ATG produces latest technology NBR gloves, and its wastewater treatment plants are designed to discharge pollutant free water to the environment. The Teejay Lanka Ltd. manufactures smart and advanced textiles, fabrics and garments. The LTL liquid sludge has been converted to iron oxide based antimicrobial pigments and bricks.

Figure 6: Advanced gloves manufactured at the ATG Lanka Ltd. (b) Advanced and intelligent textiles, fabrics and garments manufactured at the Teejay Lanka Ltd. and (c) Antimicrobial pigments and bricks manufactured from the LTL Galvanizers liquid sludge.

The green coating market is developing, and zero volatile organic compound (VO) coatings are becoming attractive. Very common VOC materials include acetone, acetic acid, butanol, carbon disulphide, ethanol, isopropyl alcohol, formaldehyde, and methylene chloride. Day-to-day consumer products also contain these VOC materials. Developing materials, devices and products without VOCs is a prime need and responsibility of the chemist.

Sustainable Development Goal 12: Responsible Consumption & Production

Responsible consumption and production are key issues addressed by the chemist. These include improved quality and efficiency of production processes, improving water stewardship efforts and energy efficiency, better and safe food packaging, and additives to prevent food loses to innovations in waste management systems. The chemical processing industry helps to reduce the life cycle impacts of consumption. The circular economy considers the reduction, reuse, recycling, and redesign of the materials. Since food packaging causes concerns such as high production volume, short usage time, waste management and littering, circular economy as regard to food packaging materials has also become an important issue. However, there are problems associated with recycling of food packaging materials. These include the increased levels of hazardous materials, after migration of components from packaging materials to food items. Geuek et al. [38] reveals the "Food packaging in the circular economy: Overview of chemical safety aspects for commonly used materials" and is an important reference to workout consequences of circular economy as applied to food packaging materials. The graphical abstract of [38] that is reproduced here in Figure (7) with permission clearly show the problems associated with circular economy of food packaging materials (left) and how to overcome these problems (right).

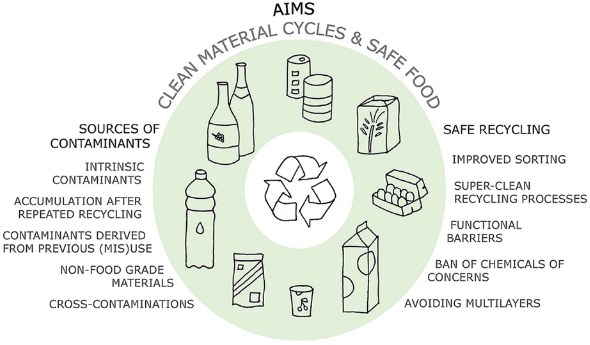

Figure 7: Problems associated with recycling of food packaging materials (left) and ways of overcoming these problems (right). Reproduced with permission from [39].

Sustainable Development Goal 13: Climate Action

The global climate change has become a serious issue potentially threatening the existence of biota including humans. Unexpected drought and flood conditions have arisen as consequences of global climate change. Atmospheric chemistry plays a major role in understanding causes of global climate change. Chemical research also enables mitigating and adapting to climate changes. The carbon footprint that is the amount of greenhouse gases released into the atmosphere as a result of the activities of a particular individual, organization, or community, plays an important role in global climate change. The carbon footprint is measured in tonnes of carbon dioxide (CO_{2}) or carbon dioxide equivalents (CO_{2e}). According to the global data obtained in 2017, the major contributors of carbon footprint are as follows [38].

- **Energy** (the burning of fossil fuels) produced 36013.52 million tonnes of CO_{2e}.
- **Agriculture** produced 5795.51 million tonnes of CO_{2e}.
- **Land-use change, and forestry** (altering or converting land) produced 3217.07 million tonnes of CO_{2e}.
- **Industrial processes** produced 2771.08 million tonnes of CO_{2e}.
- **Waste** produced 1560.85 million tonnes of CO_{2e}.

As we see, there are only a few industries casing the major fraction of the carbon footprint. Therefore, taking remedial measures such as switching to green energy resources, safe and green agriculture, responsible land and forestry use, green industrial processes and responsible waste management are important in controlling the carbon footprint to preserve the planet for future generations to survive.

Finally, the ACS Green Chemistry Institute presents "Design Principles for Sustainable Green Chemistry & Engineering" [39]. It emphasizes the following green chemistry goals.

- Maximization of Resource Efficiency.
- Elimination and minimization of hazards and pollution.
- Holistic design systems and use of life cycle thinking.

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Professor R.M.G. Rajapaksha, *Senior Professor in Chemistry attached to University of Peradeniya, Sri Lanka, and Coordinator and Consultant in Nanotechnology Degree Programmes of Sri Lankan Universities and for 10 Sri Lankan industries. Prof. Rajapaksha hold a First Class Honours in B.Sc. Special Degree in Chemistry with Pure Mathematics as the subsidiary subject (University of Peradeniya 1979-1983) and a Ph.D. and D.I.C. from Imperial College of Science, technology and Medicine, University of London, UK (1985-1988).*