“Polymer processing development towards environmental sustainability goals: An Overview”

(Plenary presentation at the 19th Asia Workshop in Polymer Processing 5th – 7th Oct, 2022)

Pak-Kuen Chan, FPRIM

Abstract:

Significant advances of polymer processing technology has been developed and adopted for the manufacturing of a wide array of products to fulfil requirement of our daily lives. Amid the increasing concerns of Climate Change and global warming, a number of approaches are underway to address this concern. United Nations members adopted in 2015 an agenda i.e. “Transforming Our World: The 2030 Agenda for Sustainable Development”. Current and future development of polymer processing should gear towards the compliance of the 17 pillars of the SDGs in combination with IR 4.0 and Circular Economy. The paper presents an overview of polymer processing development which takes into consideration of environmental sustainability amongst others. This includes but not limited to smart manufacturing, green polymers, 3D printing, biodegradable plastics, polymer master-batching, smart polymers and latest development not forgetting environmentally friendly manufacturing process using renewal energy e.g solar, wind, biomass, low carbon footprint and recyclability.

Introduction:

It is recognised that polymer is one of the most significant achievements of Chemistry; and to-date it remain one of the well-researched material. In tandem, marked advances of polymer processing technology has been developed and embraced for the manufacturing of a wide array of products to fulfil requirement of our daily lives. However, existing polymer processing technology previously developed might have overlooked or somewhat ignored the elements of environmental sustainability leading to the generation of abundant wastes e.g. the single-use plastics of which environmental pollution and recyclability being the challenges.

Polymers & Processing principles

Polymers are very large molecules made up of repeating smaller and simple chemicals to form very long molecular chains which are elastic by nature. Some polymers occur naturally e.g. natural rubber, silk etc. while others are man-made e.g. polyethylene, polyamide etc.

Pak Kuen CHAN (PK)

40 + years of technical & operation experience in rubber manufacturing industry starting his career in Revertex Ltd, which is an international rubber latex/polymer emulsion manufacturer. Last employment was Weir Minerals Malaysia (former LINATEX Rubber), a leading global supplier of rubber products for the mining and aggregate industry. Positions held include Divisional head of Research & Technology and Global Rubber Technical Consultant.

Presently working as freelance rubber consultant; part time lecturer at PRIM, Akademi Hevea Malaysia (MRB), and PGRT program at UniKL.

Acquired the Licentiateship of the Plastics & Rubber Institute (LPRI) London and Master degree in Business Administration (MBA) from University of Strathclyde, Scotland.

Training competency include Dry Rubber Manufacturing Operation under Human Resource Skill Development Department. Also a Certified and Accredited Trainer under Human Resource Development Corporation.

PK was awarded Fellowship of the PRIM and has served as the President of the Institute for 6 terms of 12 years.

Polymers in general are classified as follows:

- Natural Polymers: They occur naturally and are found in plants and animals
- Semi-synthetic Polymers
- Synthetic Polymers
- Linear Polymers
- Branched-chain Polymers
- Cross-linked Polymers
- Classification Based on Polymerization
- Classification Based on Monomers

Polymer Processing

Polymer processing is defined "*An engineering activity concerned with operations carried out on polymeric materials or systems to increase their utility*" - *Algae Based Polymers, Blends, and Composites, 2017*

Polymer processing technology which is typically undertaken prior to shaping process has shown remarkable progress with the development of synthesis methodologies, materials properties characterization, and their ultimate applications. The bulk of the polymer processing industry is in the production of **films** and **sheets** of thermoplastic polymers. Products are primarily used in the packaging industry for either foodstuffs (groceries, dairy produce, etc.) or other consumer products. There exists a wide spectrum of processing equipment which include Single and twin screw extruders, Injection moulding machine, Batch mixers, Roll mills, Calenders and so on.

Typical polymer Processing Operations

Polymer processing involves all or some of the operations e.g. handling of particulate solids; melting or heat softening; depends on the thermal and physical properties of the polymer (T_g, T_m,) degradation temperature; pressurization and pumping; transporting the melt to the shaping operation largely depends on the polymer rheological characteristics; mixing for melt homogenization or dispersion of additives. There are many other operations which include die forming, moulding and casting; secondary shaping (e.g. Thermoforming, blow moulding; calendering and coating processes.

Environmental Sustainability & Concerns

The scope of environmental sustainability for polymer processing is fairly wide ranging but, in general, it essentially incorporates the following practices:

(i) Effective management of resources;

(ii) Environmental protection,

(iii) Waste reduction, and

(iv) Avoidance of hazardous materials to ensure our future generations of humanity continue to enjoy an acceptable quality of life on earth.

All the above would certainly help in contributing to the reduction of Climate change and Global warming which relates to greenhouses gases emission and environmental pollutants. This is especially critical amid the current natural resources depletion, solid wastes accumulation from both industry and domestic consumption. In recent years, Climate change and Global warming concern have escalated as evidenced by increasing Government and Corporate's focus on environmental sustainability compliance.

Polymer processing: Sustainability Compliance

Current and future polymer processing development shall be guided and governed by several environmental sustainability objectives. Some of which to be discussed as below:

a. Sustainable Development Goals (SDG)

b. Industry Revolution $^{4.0}$ (IR $^{4.0}$)

c. Environmental Social & Governance (ESG)

d. Circular Economy

a. Sustainable Development Goals (SDG)

IN 2015, the United Nations adopted 17 sustainable development goals (SDGs) to be achieved in 2030. SDG is an interconnected strategy for the promotion of sustainable practices and solutions. SDGs aim to address pertinent issues as below faced by our society. Two emerging topics i.e. Circular Economy (CE) and Industry 4.0, are currently gaining interest and would contribute to meeting SDG goals.

b. Industry Revolution 4.0 & its relevance

The concept of IR 4.0, first incepted in Germany around 2012, involves technological innovations in the fields of *automation* and *information technology* for manufacturing. Its basic objective is the creation of faster, flexible and efficient processes; which are clearly relevant to polymer processing development. It further promotes the union of physical and digital resources, connecting machines, systems and assets in order to produce higher quality items at reduced costs. It is necessary to generate a high level of articulation between the main technologies that form the concept comprising the 9 pillars. They are Big Data & Analytics; Robotics; Simulation; Horizontal & Vertical Integration; Internet of Things (IOT); Cyber security; Cloud Computing; Additive Manufacturing and Augmented Reality.

Source: https://www.dreamstime.com

IR 4.0 is recognised as a platform for transforming the operation potential of manufacturing industries. In 2018, Hj. Nik Rosdi Nik Yusoff, a director for Productivity & Competitiveness Development of Malaysian Productivity Corporation highlighted a concern: "… ***the issue of Malaysia's low productivity growth was of concern to us, as the level of productivity growth was stagnant in 2017"***

Hence, IR 4.0 is to be adopted and embraced by manufacturing sectors which include Polymer processing to boost productivity growth with sustainability compliance.

C. Environment, Social & Governance (ESG)

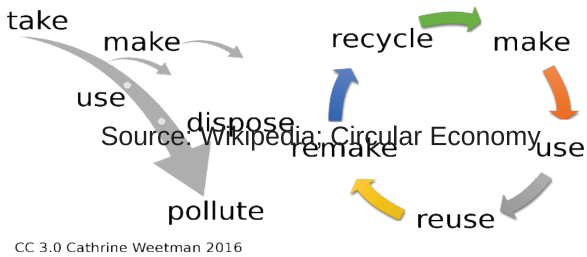
ESG is a set of standards measuring a business's impact on Environment, Social and Governance; the latter relates to how transparent and accountable it is. In recent years, a number of Malaysian companies were investigated for apparently noncompliance to ESG. Their products were held up at US ports by the US Customs and Border Protection (CBP) on allegation of ''forced labour'' or excessive overtime in their production. One oil palm plantation group was also blacklisted for alleged infringement to environment sustainability associated with de-forestation, rightly or wrongly!

While SOCIAL which covers diversity, equity, human rights & labour standards, good health/wellbeing etc. and Governance which focuses on reporting and Transparency etc., ENVIRONMENT encompasses **Sustainable Ecosystem, Waste Management, Water Management & Efficiency, Responsible Consumption & Production, Renewal Energy, and Energy Efficiency**

ESG is increasingly relevant to polymer processing in terms of Capacity building initiative, which is key factor driving the journey towards a sustainable economy. The adoption entails a multi-disciplinary approach to research program, new technology, R&D upscaling.

d. Circular Economy

Polymer processing approach towards Circular Economy is transformed from Linear Economy which is designed with little concern of ecological footprint. The figure below is an illustration showing the difference between the '*'take – make - waste*'' of Linear Economy practice and the Circular Economy approach covering "***make** – use – reuse -remake – recycle – **make***"



The model of production and consumption involves sharing, leasing, re-using, repairing, refurbishing and recycling existing materials and products as much as possible. This in turn aims to tackle global challenges associated with climate change, biodiversity loss, wastes and pollution. Hence, the core values encompass:

- eliminating waste and pollution
- circulating products and materials
- regeneration of nature

Carbon Boarder Adjustment Mechanism (CBAM)

CBAM is another environmental practice need to be brought into attention during polymer processing development. EU has recently extended this climate change initiative to the rest of the world by putting a price on imports to reflect the Carbon embedded in them. It is a proposed carbon tariff on **carbon intensive products**, such as cement and some electricity, imported by the European Union. The transition to a low-carbon economy requires technology and investment beyond the resources of many countries. Proposed solutions include technology transfer and Green Finance. Presently CBAM appears to have no immediate impact on polymer sector, but all future development needs particular focus on CBAM compliance.

Polymers: *Go Green, go Natural !*

There are essentially two classes of sustainable polymers i.e. **Natural** and **Green** polymers. Although both appears synonymous, there are some differences:

Natural Polymers:

Natural polymers exist naturally or are produced by living organisms (such as cellulose, silk, chitin, protein). They can also be man-made out of raw materials. However, it was reported the amount is less than 1% of the 300 million tons of plastics produced per year despite production is steadily rising driven by market demand for a variety of applications.

One most notable ''Natural Polymer'' is Natural Rubber derived from Hevea Brasiliensis (1.4 cis polyisoprene). NR is a well-recognized renewable resourceS par excellence. NR plantation is a carbon dioxide sink and a carbon dioxide scavenger. Enormous quantities of CO_2 are emitted during the manufacturing process using petroleum-derived synthetic rubber as the raw material especially for car tires manufacturing. Replacement with natural rubber would confer low carbon footprint that prevents global warming. Other NR alternatives being looked into by major tyre manufacturers include Guayule, Russian dandelion, Gutta Percha, Balata etc.

Hevea Brasiliensis

Guayule

Russian Daendelion field

Bio-based polymers which could be classified ~~a~~ Natural Polymers are defined as materials of which at least a portion of the polymer consists of material produced from renewable raw materials. For example, bio-based polymers may be produced from corn or sugarcane. The remaining portion of the polymers may be from fossil fuel-based carbon. Bio-based polymers generally have a lower CO_2 footprint and are associated with the concept of sustainability. For example, a most recent report that a Japanese sports gear maker, Asics, has successfully developed sneakers made with plant-based polymers which contains the lowest carbon footprint with reduced carbon dioxide emission of 1.85 kg of CO_2 during their lifetime. (Ref: Nikkei – 09 Oct, 2022)

- **Green Polymers**

Green polymers are produced using green (or sustainable) chemistry. Green chemistry relates to the *"design of chemical products and processes that reduce or eliminate the use or generation of substances hazardous to humans, animals, plants, and the environment"* (IUPAC 1990)

Hence, polymer processing shall fulfil the green principles which include a high content of raw material in the product. The production must be clean and generate zero waste coupled with low carbon footprint without the use of additional substances e.g. organic solvents. It should incorporate high energy efficiency during polymer manufacturing and absence of health and environmental hazards.

Bioethanol is considered an example of a Green Polymer. It is an emerging biofuel, produced by fermentation of sugar obtained from sugar cane or cellulose; and also a versatile raw biomaterial for production of olefin and di olefin monomers, including ethylene, propylene, and butadiene

Smart Manufacturing

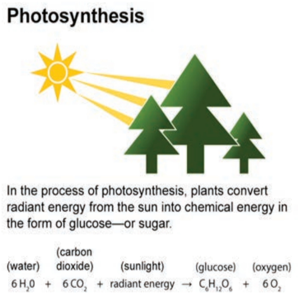
Smart Manufacturing is a broad category of manufacturing with the objective of optimizing concept generation, production, and product development. As mentioned earlier, IR 4.0 is a tool which drives towards Smart Manufacturing. The interaction of IR 4.0 and Smart Manufacturing contribute to a fully integrated, collaborative manufacturing system which respond in real time in operating condition, supply network and customer needs. Further, it tends to drive innovation, technology and human creativity addressing:

- Wastes reduction
- Reduction of energy consumption
- Minimising environmental impact via reduced

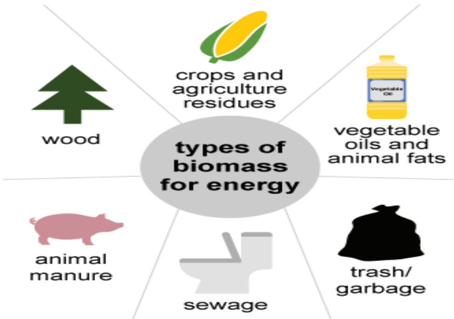
energy consumption aiming increased productivity

Biomass—renewable energy

Biomass is commonly derived from organic material that comes from plants and animals. This was used to be the largest source of total annual U.S. Energy Consumption and today remains net exporter of biomass energy. Biomass energy continues to be an important fuel in many countries and helps mitigate the effects of climate change. Biomass provides excellent feedstock for the synthesis of useful **monomers**. Sustainable polymers from biomass can be obtained through chemical modification of natural polymers, such as **starch, cellulose, or chitin**



Source: The National Energy Education Project



Source: U.S. Energy Information Administration

3D Printing for Polymer Processing

3D printing, also known as Additive Manufacturing, is one of the 9 pillars of IR 4.0. This is a technology of creating a three dimensional object layer-by-layer using a computer created design. It is described as an additive process whereby layers of material are built up to create a 3D part. As compared with Subtractive Manufacturing process i.e. final design is cut from a larger block of material. Hence, 3D printing creates less material wastage**.** Other advantages include Flexibility and Creativity during designing process. However, current limitations include being not conducive for mass production nor suit every type of manufacturing technique. Furthermore, hardware & materials are at present relatively price prohibitive.

A study on Fused Deposition Modeling (FDM) has recently been undertaken by Malaysian Rubber Board, presented at recent RubberCon 2022 by Dr Yen Wan Ngeow (Roland), Senior Research Officer. Project objective is, in summary, to evaluate the effect of infill densities and patterns of Thermoplastic Polyurethane (TPU) in comparison with conventional compression molding process

It was reported **4D applications** arising from 3D printed objects are the new normal for Additive Manufacturing technique as researchers are focusing on exploration of smart material matrix to address different targeted applications such as for drug delivery, sensor applications and self-assembly applications etc (Gao *et al*., 2016; Kumar *et al*., 2020b)

Polymer master-batching

Master-batches or polymer bound additives are commonly used in polymer processing. This entails the incorporation of color pigments, additives and antimicrobials into the polymer resin or other liquids. Concentrated mixture of an additive is encapsulated in a carrier material or binder, such as PE or PP. The benefits include safe handling of hazardous materials, cleaner production, easier addition of ingredients, product and process consistency, consistency and stability. While the material costs are relatively higher than the powder counterparts, there is strong justification using polymer bound additives for future polymer processing for cleaner and safer operating environment with reduced chemical loss.

Smart Polymers

Smart polymer embraces a wide range of different compounds that can change their color, transparency or shape in response to their environment. They are smart because of their ability to respond in significant way when small environmental changes are detected**.**

It only takes a small variation in temperature, humidity, pH, or light, for example, to induce a large change in smart polymer properties, and this non-linear response makes them unique. Smart polymers may fall into one of three groups:

- **Physical** – temperature, ultrasounds, light, or mechanical strength.
- **Chemical** – pH and ionic strength
- **Biological** – enzymes and biomolecules

Renewal Energy

"Renewable energy is energy that is collected from renewable resources that are naturally replenished on a human timescale. It includes sources such as sunlight, wind, the movement of water, and geothermal heat" – Wikipidia

Manufacturers are increasingly developing new ways of using renewable energy to strengthen clean energy competitiveness in various industries. One of which is p*olymer composites in Wind Energy application e.g. wind turbine blades,* which are light and robust replacing the metal counterparts and hence significant energy saving.

Biodegradable plastics

Plastics are ubiquitous in our daily lives but not easily biodegradable and hence posing threat to environment and our health. Biodegradable plastics degrade into water, carbon dioxide, and biomass in given time frame causing generation of micro-plastics which ultimately harm aquatic life when discharged into ocean. However, not all bioplastics are completely biodegradable. An example of a non-biodegradable bioplastic is bio-based PET. Presently, a relatively small percentage of biodegradable plastics of total global production being produced, which include Oxo-degradable and Hydro-degradable.

Biodegradable polymers are poised to revolutionize from food packaging to medical devices. Some commercial biodegradable plastics are polybutylene adipate terephthalate (PBAT) and polyvinyl alcohol (PVA).

There is another category known as Photodegradable plastics which is copolymer of ethylene with carbon monoxide. They contain ketone groups that absorb sufficient energy from sunlight to cause extensive polymer chains shortening or scission.

Disruptive Technology

Last but not least, Disruptive Technology is something that cannot be ignored by technologists and engineers in future polymer processing aiming environmental sustainability. This is essentially a revolutionary approach that significantly alters the way that consumers, industries, or businesses operate. It leads to new and enhanced technology that displace established practices, rendering them obsolete. This leads to creation of new products, processes, new market and new ways of conducting business. There has been a number of Disruptive Technology in recent years e.g. 3D Printing, 5G, Improved Connectivity, Artificial Intelligence and Machine Learning, Automation and Robotics. Most notably disruption being taxis having been replaced by E-Hailing not forgetting E-Commerce which partially substitutes traditional retailing business, if not completely in the future.

My limited experience in Disruptive Technologies for rubber product manufacturing are briefly described herewith:

a. Manufacturing of Conveyor beltings or rubber sheeting of continuous length.

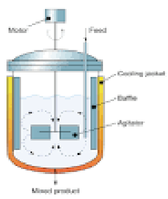
Conveyor belting and rubber sheets of continuous length are traditionally produced using Compression Moulding press which employs Step-Curing protocol. This has been replaced by, initially, Rotor Cure and later the ''Double Belt continuous curing press'' which incorporates a ''roller carpet'' technology first patented in Germany.

VS.

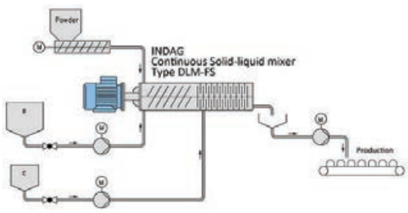
Tradition Compression Press
Source: Simpelkemp Double-Belt Press for continuous curing

b. Continuous mixing of Liquid to Solids or Liquid to Liquid replacing Batch Mixing process.

Batch Mixing



VS.



Source: **INDAG** *Continuous mixing of liquid-solids compound*

Outlook

Future polymer technologists/scientists need to define/

predict the complex inter-relationships between process equipment, operating conditions, micro- or macro-structure arising from polymer processing. They need to acquire further understanding of engineering principles e.g. transport, mixing, solid mechanics, rheology), polymer physics & polymer chemistry to accomplish any designated tasks; while ensuring the availability of improved computer-aided design software for:

– mould or screw design cavity filling simulation,
– flow calculations and process simulation

Multicomponent polymer systems (blends, alloys and composites) are expected to continue expanding the horizons of product concepts and novel applications during the next decade.

Conclusion

Escalating environmental concerns e.g. Global warming and Climate Change, warrant Polymer Processing development to adopt a holistic approach by embracing SDGs, IR 4.0 and ESG. SDGs encompass Circular Economy and Smart/Sustainable Manufacturing which contribute to waste reductions, lower carbon footprint and hence environmental protection. In line with such practices and compliance, polymer processing plants, if not already done so, need upgrading to meet future environmental challenges and requirements e.g. use of feedstock of more environmentally friendly and renewable resources. Polymer technologists need to continuously innovate by observing Disruption Technology that could displace existing technologies rendering them obsolete. They must be sufficiently competent to define and predict the complex interrelationships of every aspect of Polymer Processing development towards environmental sustainability goals.

References:

1. MARINO XANTHOS, in Applied Polymer Science 21st Century, 2000
2. H. N. Cheng *, Southern Regional Research Center, USDA Agriculture Research Service, Louisiana 70124, US.
3. Elsevier :https://www.sciencedirect.com/science/article/abs/pii/
4. Wikipedia.org/wiki/Carbon Border_Adjustment_ Mechanism
5. US Energy Information Administration (www.eia.gov/energy explained/biomass//
6. Polymer Solution Incorporated: *Materials Science Research & Innovations* January 28, 2014 /
7. Akzo Materials, Kerry Taylor-smith Sept 4th 2019
8. Wilkipidia: Circular Economy
9. Donald G. Baird, in Encyclopadis of Physical Science and Technology (3rd Edition)
10. Omnexus, Growing Role of Polymers and Plastics Used in Renewable Energy Sector