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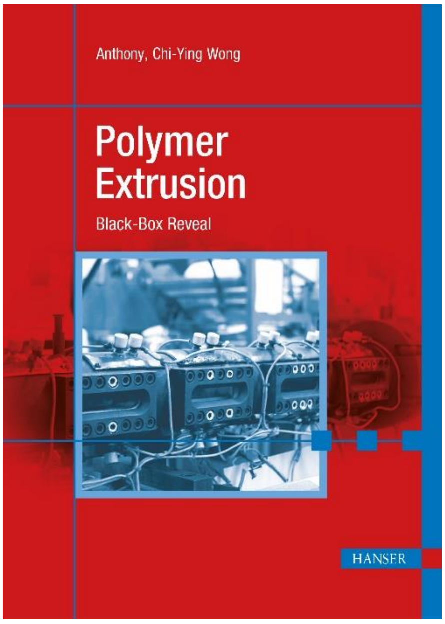


# Sample Pages

# Polymer Extrusion

Anthony, Chi-Ying Wong

Print-ISBN: 978-1-56990-917-1
E-Book-ISBN: 978-1-56990-938-6

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# The Author

Dr. Wong's academic journey began at the University of Bradford, where he obtained a B.Tech (Hons) degree in Chemical Engineering. Building upon his passion for the field, he pursued further education and successfully completed his Ph.D. in Gas Fluidization of Cohesive Powders, further specializing in the realm of chemical engineering.

After completing his studies, Dr. Wong ventured into the corporate world, gaining valuable experience in the plastics industry. He worked with BASF and Exxon Chemical, where he held technical and marketing support roles within their plastics divisions. This hands-on experience allowed him to develop a deep understanding of the industry's dynamics and challenges.

Driven by his passion for knowledge dissemination and academic pursuits, Dr. Wong transitioned into academia. He joined the Department of Industrial and Manufacturing Systems Engineering at The University of Hong Kong, where he contributed to the advancement of research and education in his field. His expertise and dedication to teaching and mentorship benefited numerous students during his tenure.

Continuing his professional journey, Dr. Wong took on a pivotal role as the vice-chairman of a listed color masterbatch compounding company in Hong Kong. In this capacity, he assumed significant responsibilities, including overseeing market development, exploring global commercial opportunities, and spearheading research and development initiatives.

Currently, Dr. Wong holds the position of Market Coordinator – Asia Pacific at Badger Color Concentrates Inc., a masterbatch manufacturing company based in the United States. In this role, he focuses on coordinating and expanding the company's business throughout the Asia Pacific region, leveraging his extensive experience and industry connections.

Dr. Wong's expertise extends beyond his commercial endeavors. He has dedicated considerable effort to conducting research studies in various areas related to the plastics industry. His primary research interests include plastics processing technology, with a particular emphasis on extrusion, as well as the rheological characteristics of polymers, biodegradable polymers, environmental engineering, and powder technology. His research contributions have been published in international journals and conference proceedings, showcasing his commitment to advancing scientific understanding and practical applications within his field.

In 2021, Dr. Wong published a book titled "Powder Technology in Plastics Processing" with Hanser Publishers, Munich. This book serves as a valuable resource for researchers in the field, offering insights into the intricate aspects of powder technology and its application in plastics processing.

# Preface

In writing this book, my primary focus revolves around two essential objectives that guide my work and aspirations.

The first objective is to share the findings of the extensive research work conducted by different researchers, including myself, on the dynamic processing characteristics of plastics extrusion. These research efforts utilized a unique visualization technique developed by Professor F. H. Zhu of Beijing University of Chemical Technology, China.

Over the years, the visualization technique has been applied to single- and twin-screw extruders. These extruders were specially designed and constructed with a series of openings along the metal barrel, each of which was covered with high-optical-quality glass. Operating these custom-built machines and conducting the required tests using this technique was tedious, demanding unwavering attention to detail and precision. However, the results obtained were nothing short of enlightening. The method, as proven through the research effort, can vividly disclose the dynamic processing characteristics of extrusion processes. Due to their inherent limitations, the work also uncovered crucial processing characteristics that had previously eluded detection in other empirical and theoretical studies. Armed with the observed data gathered through these visualization studies, we can now provide qualitative descriptions and a profound appreciation for the dynamic processing characteristics, which hold immense practical significance. Furthermore, the observed features, made visible through the glass openings, have the potential to significantly contribute to the development of more realistic and comprehensive theoretical processing models. By incorporating these newfound insights into theoretical frameworks, we can enhance our understanding of plastics extrusion, leading to improved processes and outcomes in practical applications.

The second objective of this book goes beyond the sharing of research findings. It aims to inspire and ignite further research endeavors in plastics processing. Through the comprehensive discussion of selected topics, this book seeks to encourage researchers to recognize the immense potential of this innovative empirical technique when applied, with the necessary modifications, to other plastics processing behaviors. By shedding light on the possibilities and benefits of employing visualization techniques in the study of plastics processing, I hope to motivate and empower researchers to explore new avenues and expand the boundaries of knowledge in this field.

Looking ahead, I envision a future that integrating this visualization technique with advancements in artificial intelligence (AI) will usher in a revolutionary era in the field of plastics processing. By harnessing the power of AI and coupling it with the insights gained from visualization studies, we can unlock a deeper and more meaningful understanding of plastic materials and processing techniques. This convergence can potentially revolutionize the industry, leading to more efficient and sustainable practices.

In essence, this book serves as a stepping-stone, paving the way for researchers and professionals to embark on new frontiers of exploration and innovation. By facilitating further advancements in the field of plastics processing, it has the potential to contribute to creating a more sustainable and efficient future, where the utilization of plastic materials aligns harmoniously with environmental stewardship and economic progress.

I am deeply grateful to Dr. M. Smith and Ms R. Wehrmann of Hanser Verlag for their unwavering support and encouragement throughout the process of writing this book. Their kindness and guidance were especially crucial when I thought of giving up. My heartfelt thanks go to Mr P. P. Rao of TechnoBiz Communications Co. Ltd, Thailand, whose invaluable experience and shared wisdom fueled my determination to continue writing.

I want to express my sincere appreciation to Professor A. Wong of York University, Canada, for his patient instruction in the fundamentals of statistics, even amidst his busy schedules. His teachings have been instrumental in shaping my understanding of statistical analysis. I am also profoundly grateful to Professor D. Geldart and Dr. N. Harnby, under whose supervision I completed my own research degree studies. Their emphasis on logical reasoning and research philosophy has profoundly influenced my approach to research. I would like to sincerely thank them both for their invaluable guidance.

My thanks also need to be extended to the dedicated students at the University of Hong Kong and the City University of Hong Kong, who played an integral role in conducting the meticulous experimental work and collecting the insightful results. Their commitment and hard work contributed significantly to the success of this research project. I am truly grateful to them for their invaluable contributions to this endeavor.

In addition, I would like to thank my parents for instilling in me a positive attitude towards life. Their unfailing support has been a constant source of inspiration for me. Finally, I am immensely grateful to my wife Sue, my sons Darren and Jens, and my brothers and sisters for their tremendous patience, encouragement, and support as I wrote this book over the months. Their understanding has helped me immensely on my journey, and I am truly fortunate to have them by my side.

Last but certainly not least, I would like to take this opportunity to express my heartfelt appreciation to Dr. David Barden of Clearly Scientific Ltd for the immeasurable assistance he has provided me. I am immensely grateful for the time and effort he has dedicated to helping me enhance my English language skills and presentation, and also refine my expression of scientific concepts.

Each of these people has played a significant role in my personal and professional development, and I am deeply grateful for their contributions. I am forever indebted to them.

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# 1 Introduction

Let's begin our discussion with the development of Western medicine.

On the civilization timeline of human history, medicine has occupied a significant proportion. This could well be due to the natural desire and curiosity of humans to explore the mysteries of life and death. Many challenging questions asked in ancient times, such as how our body works and how our bodies recover from diseases and injuries, remain unanswered today.

The history of medicine can be traced back to some 5000 years ago when our ancestors attempted to understand the causes of illness and disease. Many of those early trials were futile, and contributions were scarcely noted. Lack of relevant medical knowledge and resources were the reasons for these inefficacious attempts performed by our ancestors. For much of our history, sickness was almost always linked to divine displeasure, and ill health was often attributed to the gods' punishment for our sins. Relating illness to punishment has since become deeply rooted in our thinking, especially throughout the early stage of our civilization.

Sitting between the so-called "ancient" and "modern" medicine is the time of **Hippocrates**. Hippocrates, who was born and lived on a Greek island around 400 BC, was a significant figure in the medical world. He was mostly concerned with the treatments prescribed primarily by shamans for the sick during his time. The practice of trepanning was one such treatment, and involved drilling holes into the head to remove evil spirits believed to be the cause of (for example) migraines and seizures. Indeed, these beliefs had a fundamentally superstitious basis, without any scientific logic.

During the time of Hippocrates, apothecaries could not be at all trusted. They were often bribed to poison their patients rather than provide appropriate treatments for getting better. Therefore, Hippocrates brought the concepts of ethics and integrity to the medical world. These concepts formed the cornerstone principles of medical practices then, and continue to the present day. Hippocrates also advocated that natural causes of diseases should be the primary focus when the origins of diseases were investigated, and he was the first to suggest a relationship between lifestyle and health. This concept has become the foundation upon which the medical world has built. Hippocrates further developed the theory of four "humors" which became the dominant explanation for causes of diseases in the 1500 years after his death. These contributions of Hippocrates have won him the respect as the "father of modern medicine" he highly deserved.

Another influential figure in medicine was **Aristotle** (384–322 BC), who came in slightly later than Hippocrates. Building upon Hippocrates' beliefs, Aristotle dug deeper into the research work on the relationship between philosophy and Hippocrates' natural causes. He later developed the idea that the liver was the organ to do with food, while the brain was to do with motion, and the heart was the source of life associated with passion and feelings.

**Galen** was born in a wealthy Greek family in Turkey in 129 AD, later in life choosing to settle in Rome. Galen received an excellent and comprehensive early education because of his family background – his father was a professional and had an extensive natural interest in science. Galen studied medicine at the prestigious Alexandria Library in Egypt, and over his lifetime wrote many books and developed many ideas and theories. Though most of them were unprecedented, some were based on or extended from the work of Hippocrates and Aristotle. He advocated treatments of the theory of opposites, which was much similar to that of the principle of traditional Chinese medicine. This theory proposed that for the universe to exist and persist, every single component must balance with each other in all aspects. Galen reckoned that this concept of balance and the theory of opposites should also apply to our bodies. For example, if a person became sick because their body was too "hot", then introducing something "cold" into the body should be the appropriate treatment, as this would restore it to its balanced state.

The results of Galen's research studies in medicine had a tremendous impact on the medical world for over 1000 years. His contributions cannot be overlooked, even though some of his work was proved, hundreds of years later, to be completely absurd and wrong. The greatest influential thought of Galen was his belief that there must be a creator in the universe. Otherwise, it would be impossible to answer why the human body had such a unique design and function. His belief held sway over the development of the Christian church, and subsequently formed the pinnacle of our medical knowledge for hundreds of years.

From the time of Galen until the modern day, the advancement of medicine has basically resulted from the successful applications of other branches of disciplines, such as chemistry, biology, and physics. These disciplines either attempted to reveal our body's different functions or offered effective treatments to cure sickness. As a consequence, the subject of medicine has become a pure science discipline, and specialization in smaller and smaller medical areas has become inevitable.

Among the many factors contributing to the advancement of medicine, the development of "tools and instrumentation" technologies cannot be neglected. These include:

- stethoscopes (to enable the sound of our body, largely our hearts and lungs, to be heard)
- sphygmomanometers (to measure our blood pressure)
- otoscopes (to enable visual examinations of our inner ear)
- ophthalmoscopes (to allow the structure of our eyes to be visually examined).

Instruments such as these have greatly enabled medical professionals to gain direct and first-hand medical information about the state of a patient. The successful applications and proven reliability of technologies such as X-rays, computer tomography, endoscopes, and imaging modalities, have contributed enormously to the modern medical world, and this seems very likely to continue. With the help of these tools and technologies, the origins of sickness in our body can now be precisely located, and treatments can be applied more effectively and with greater precision to the affected areas. These successes have led to the establishment of many sub-specialties within the medical world. Alongside these developments, surgical science has gradually become an important integral part of modern medicine, by providing patients with alternative treatment options.

The big leap in medicine has been, as discussed, a collective input of many different disciplines, including chemistry, bacteriology, and others. However, technological breakthroughs enabling us to "communicate" directly with the different parts of our body make an equal contribution. Using specific devices or performing surgical procedures for precise diagnoses and treatments has made these communications possible, with some even enabling direct visual observation. Without these breakthroughs, our body would have remained a complete "black box", and any treatments would have still involved a great deal of guesswork. Because this is not the case, we can largely avoid incomplete or even incorrect treatments and diagnoses. It has been envisaged that technologies capable of offering visual examinations and treatments will dominate medicine in the future. Artificial intelligence has already proved to be a useful tool for achieving safer and more effective medical care.

If the analogy of a human body to a "black box" is extended to plastics processing, a clear resemblance between the two subjects can be seen. When metal barrels are involved in any plastics processing equipment (such as an extruder or an injection molding machine), we only know, as depicted in Figure 1.1, what goes into the processing equipment and what comes out downstream of the processing line. We have no idea what happened in the barrel. With such a hardware setup, successful analyses of the processing behaviors inside the barrel will inevitably require "intelligent guesswork". Questions such as how the solid materials are conveyed and mixed, how the melting mechanism exactly takes place, how the molten phase polymer mixes with solid additives (if any), how the colorants are dispersed or distributed during processing, how screw configurations affect the processing mechanisms, etc., cannot be answered accurately and convincingly without any evidence or data obtained directly from the inside of the "black box", i. e., the barrel.

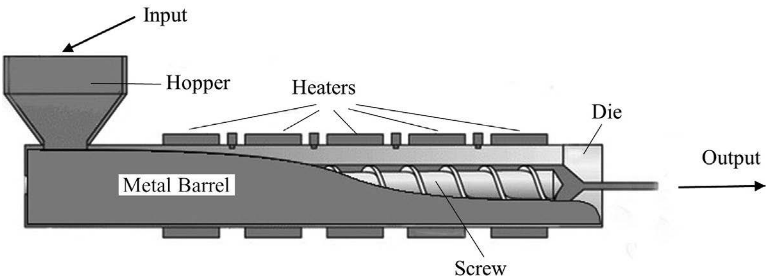


**Figure 1.1** Schematic diagram of a typical single-screw extruder

The main objective of any plastics process is straightforward. It simply aims to convert raw materials to finished products. A comprehensive structural breakdown of the conventional plastics processes suggested by Tadmor and Gogos [1] was schematically described by Wong [2], as shown in Figure 1.2. It can be seen from the figure that successful conversions will depend on our understanding of the principles of multiple engineering and scientific disciplines such as transport phenomena.

The elementary processing steps suggested by Tadmor and Gogos are merely designed expectations. To prove whether these functional processing characteristics exist according to the design anticipations is most challenging, because the non-transparent metal barrel hinders direct visualization. Therefore, analytical attempts to try to reveal the dynamic functional processing characteristics must rely on indirect empirical approaches or be based upon theoretical analyses. But such analyses often lead to complicated mathematical models or expressions that can be difficult to understand.

In 1991, Zhu and Cheng [3] and Feng et al. [4] developed an empirical visualization technique that enabled the "true" dynamic processing characteristics of single-screw extrusion to be investigated. Their method involved a single-screw extruder with a number of openings "cut" along the axis of the metal barrel. Each opening was covered with a glass of high optical quality to permit direct visual observation with the naked eye. This development has since advanced our knowledge of "true" dynamic extrusion processing behavior, proving the value of the statements "what we see is what we get" and "seeing is believing".

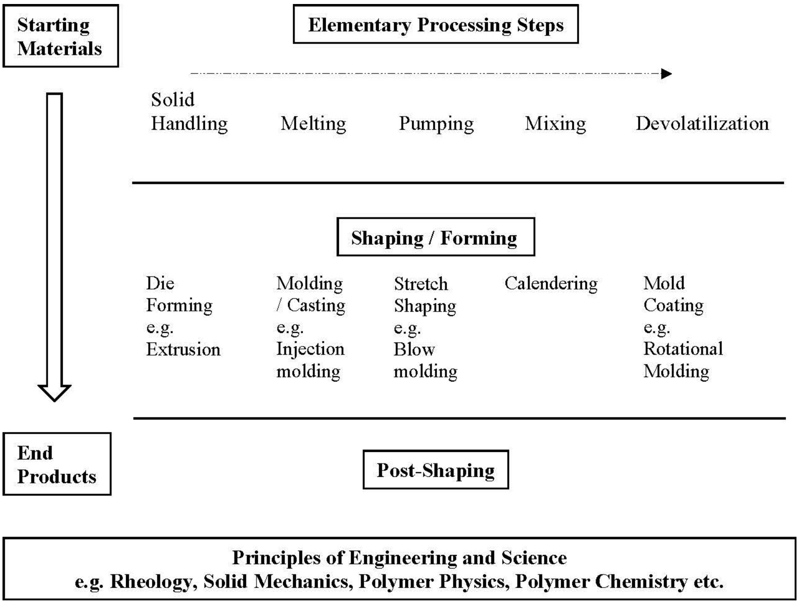


**Figure 1.2** Structural breakdown of conventional plastics processes suggested by Tadmor and Gogos [1] (Wong [2])

This pioneering work of Zhu and co-workers was followed by a series of similar research studies on the same subject carried out by Wong and co-workers (e. g., [5]). They have also extended their research effort to twin-screw extrusion (e. g., [6]). Importantly, these investigations offer a physical picture of the characteristics of the dynamic extrusion process, enabling it to be appreciated without having to solve complicated mathematical representations or make educated guesses.

The discussions in the first few chapters of this book extend beyond the topics related to the fundamental scientific and engineering aspects of plastic materials and processes, but also touch upon the markets of the plastics industry and their impact on the global economy. The subsequent chapters will focus on the qualitative depiction of the dynamic extrusion behaviors observed from the visualization technique in both single- and twin-screw extrusion. Parallel to these discussions, conventional theoretical descriptions and simplified mathematical treatments of plastics extrusion processing will also be presented. This structure will provide a basic yet comprehensive reference platform for those who may wish to continue working on the subject further.

Finally, this book will discuss the research results obtained from studies of the various extended applications of the visualization technique in the plastics processing industry. It is the author's opinion that such discussions may inspire further development of similar research investigations to be pursued.

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# 2 Polymers, Markets, Applications, and Additives

## 2.1 Introduction

Parkesine was the first human-made plastic, and since it was exhibited at the Great International Exhibition in London, in 1862, parkesine and other plastics have had tremendous success for over 150 years, along with the improvement in living standards of mankind.

Plastic materials possess versatile physical characteristics, excellent processability, and a remarkable ability to accommodate additives, giving them a vast spectrum of applications, including in every industrial sector. For example, food packages made of plastic resins can lengthen the shelf life of foods because of their excellent barrier properties. Appropriately designed plastic components in vehicles can reduce weight, saving energy without compromising safety requirements. The application of mulch films made from specially formulated plastic resins may increase agricultural yields by creating a microclimate under the films in an open field for the plants to grow in unfavorable climatic conditions. Items ranging from simple tubing and surgical masks to artificial human body parts (such as hip joints, etc.) find wide application in medicine.

These successful applications of plastic materials have brought us convenience, comfort, safety, and enjoyment. Despite these contributions to improving our quality of living, the increasing impact of plastics on the environment has, on the other hand, become an urgent challenge in recent years. Many countries have already started implementing various rules and regulations to restrict the use of plastics, which is important given the huge volume of plastic waste that is currently produced annually (estimated to be about 300 million metric tonnes). This figure could even rise to 1.2 billion metric tonnes per year by 2060 onwards – a figure that is indeed alarming, being four times more than at present [1, 2].

In 2019, 170 countries [3] had pledged to “significantly reduce” the use of plastic, with 2030 as the target year. However, many had already begun their reduction programs prior to 2019. Below is a selection of actions declared by some of these countries, many of which relate to single-use plastic (SUP):

**United States**

- California implemented a ban on using plastic bags in 2016. They further imposed regulations to restrict the use of drinking straws in 2018, with shops and restaurants only being allowed to provide drinking straws upon request.
- In 2020, New York State joined California to ban plastic bags. They further aim to impose a ban on plastic items in hotels in 2024 and to implement plastics recycling laws in 2030.
- Despite the efforts of individual states, one thing to note is that there is no country-wide ban on using SUPs.

**European Union**

- The European Union started banning SUP in 2021. In the same year, a tax on plastic packaging was implemented.

**China**

- China is the largest consumer of SUPs in the world. In 2019, it converted about 27 million metric tonnes of plastics to SUP items such as shopping bags, cutlery, etc. However, drinking straws in restaurants were wholly banned from use in 2020, and shopping and carrier bags must be made of biodegradable plastic resins from 2022.

**Kenya**

- The country has taken a very responsible attitude towards reducing the usage of plastics. In 2017, it banned SUP bags, and even bringing SUP items into conservation areas was not permitted.

**United Kingdom**

- A tax on plastic shopping bags was implemented as early as 2015. Since 2018, the government has been carrying out a stepwise implementation of other taxes on using different plastic items (as packaging materials).

**India**

- Although a ban on the use of SUP items began in 2022, the government has emphasized reinforcing the existing regulations relating to the manufacturing and storage of SUP items.

**Canada**

- A ban on SUP items was introduced in 2021, and it has the goal of having zero plastic waste by 2030.

**Thailand**

- Further restrictions on selling plastic bags in major shops and department stores have been in place since 2020. It also aims to eliminate the littering of SUP items in the ocean by 2025.

**Other countries**

- Contributions to the global effort of achieving zero plastic waste by 2030 include:
  - Japan implemented a plastic bag tax in 2020
  - Spain will have a plastic packaging tax in 2023
  - Australia started a SUP ban in 2021.

The concept of the “5 Rs” (Recycle, Recover, Replace, Reduce, and Reuse) has also been advocated by various governments and the plastics industry. However, there are increasing calls to develop “fossil-free” plastic materials, or plastic materials that can degrade. A considerable challenge in meeting this request is the lack of unanimous agreement on the definition of the terms such as “bio-based” and “degradable”. As a result, these terms have been used loosely in different industries, leading to ambiguous communications.

For simplicity, this book will refer to those plastics derived from fossil petrochemical materials such as oil or natural gas as *petroleum-based plastics*. If the plastic materials are derived from renewable sources such as starch, gluten, etc., they will be termed *bio-based plastics*. Plastic materials that can degrade are referred to as *degradable plastics*. If the degradation is caused by micro-organisms, it is termed *biodegradable plastic*. However, a further point to note here is how to define degradation. The plastic itself can naturally “degrade” but over an unacceptably long time, so information on the conditions applied to determine the degradability must be reported. The standard methods EN 13432, ASTM D6400, ASTM D5988, and ASTM D6691 are commonly used in industry to achieve this, and each has its particular test methods and conditions.

Another point to note is that a bio-based plastic material can be either degradable or non-degradable – it is the origin of the base materials that make up the plastic that matters. Further confusion is caused by the terms such as “compostable”, “non-compostable”, “oxo-degradable”, etc., as they are used so interchangeably in different industries.

It is interesting to note that the first bio-based plastic material can be traced back to 1500 BC, during the time of Mesoamericans. Parkesine, the first man-made plastic exhibited in London in 1862, was also bio-based (by the above definition), as it was made of cellulose. The first biodegradable plastic material, known as Galalith, was invented in 1897 by a German chemist. Later, polyhydroxybutyrate (PHB) was developed in France by Maurice Lemoigne in 1926. Since the biodegradable characteristics of PHB were more commonly known than those of Galalith, PHB received much more attention than Galalith, and hence broader applications of PHB have been successfully developed.

The history of the development of bio-based and degradable resins show that these materials existed long before pollution problems had become severe environmental issues. But surprisingly, the penetration of these materials into the plastic market has been very small (less than 8%). Possible reasons include the following:

- Bio-based plastics and degradable plastics are more expensive than conventional petroleum-based plastics (up to three-fold). There is therefore no economic incentive to use them.
- The physical and mechanical properties of bio-based plastics and degradable plastics are significantly inferior to those of conventional petroleum-based plastics. This intrinsic disadvantage dramatically limits their applications.
- General practice in the plastics industry has often been based on the concept of substitution when selecting materials for specific designs and applications. Therefore, only bio-plastics with characteristics similar to those of conventional petroleum-based plastics would have a chance to be selected. If such practices continue, it will be difficult for bio-based and degradable plastics to enter the market.

A point to emphasize here is that conventional marketing messages are no longer appropriate for promoting this branch of relatively new materials. Instead of using the traditional mix of marketing of, say, the four "P"s (i. e., product, place, price, and promotion) for carrying out marketing activities, a completely new combination of marketing imperatives are needed which should take into account the concept of "future", "responsibility", "sustainability" and so on.

## 2.2 The Market

The global economy has undoubtedly been adversely affected by the impact of COVID-19 since late 2019. At the time, there were many unanswered questions. How did the virus originate? What carrier did the virus need to spread itself around? When would reliable vaccinations be available? When would effective drugs be ready to cure the disease?

All these questions temporarily caused us to lose our direction and vision of the future. With numerous uncertainties every day, we all lost our momentum to go forward, and everything around us appeared to either stand still or even go backward. However, medical advice from those in authority gradually restored our "driving force". We learnt that personal hygiene and social distancing would be simple and effective means to stop the chain of infection, and we started accommodating these new habits. These included wearing face marks almost all the time (including in offices) and avoiding going to crowded places such as restaurants.

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