IAEA
International Atomic Energy Agency
Atoms for Peace and Development

NUclear TEChnology for Controlling Plastic Pollution

NUclear TEChnology for Controlling Plastic Pollution (NUTEC Plastics)

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Executive Summary

Plastics are indispensable to modern life. Plastics generate multiple benefits and conveniences, yet the vast quantities of plastics produced and eventually discarded are harming ecosystems with grave implications for biodiversity, food safety and ultimately human health. Approximately 70% of all plastics produced to date is now waste and only 9% of this has been recycled.

In many places around the world, plastic waste is mismanaged, ending up in unregulated landfills or open dumps, from where it enters oceans via rivers, waterways, or is transported by wind or tides. Plastic waste pollution is not limited to oceans only, but also can pollute terrestrial environments such as soils, and groundwater. Plastic is by design durable and this longevity means that even as waste, it does not decompose. When it reaches the oceans, it can remain there for hundreds of years, and over time it fragments and becomes micro- and nanoplastic which can enter the food chain more easily due to its small size. Ultimately, plastic does not disappear but rather accumulates in the oceans over time. On current trends, the oceans are expected to contain one ton of plastic for every three tons of fish by 2025, and by 2050, there will be more plastic than fish.

__What is NUTEC Plastics?__ The objective of NUTEC Plastics is to assist the IAEA Member States in integrating nuclear and nuclear derived techniques in their efforts to address challenges of plastic pollution. NUTEC Plastics builds on a portfolio of IAEA research and technical cooperation projects around plastic recycling using radiation technology and marine monitoring of microplastics using isotopic tracing techniques. NUTEC Plastics positions the IAEA on an important issue of global concern: __plastic pollution__. The document at hand pulls together what the IAEA can offer and where it can add value using nuclear and nuclear-derived techniques, and it spells out a set of activities complementing national and international efforts already under way. NUTEC Plastics is based on the latest technical, scientific, and economic knowledge about the plastics value chain and the transition towards a circular economy for plastic. NUTEC Plastics seeks to engage and expand the dialogue with Member States, partners, industry, and civil society. It provides a vision for the solutions that the IAEA offers to better manage plastic waste. Implementation of specific activities will happen through established IAEA delivery modalities such as Technical Cooperation projects, coordinated research projects and other programmatic activities.

There are many reasons why only 9% of all plastic has ever been recycled, the main one being the cost of the recycling process. In addition, some plastics have multiple layers of different types of plastic, or they are meshed with other materials, making recycling particularly complex and therefore expensive. Although the problem of plastic pollution is increasingly receiving global attention, the international response has largely been piecemeal and ad hoc to date. Gaps in addressing plastic pollution relate to lack of sufficient awareness, knowledge, policy, technology and financing.

The **linear model of plastic production, use and disposal is unsustainable**. A global approach is needed that establishes a circular economy and focuses on the '4Rs': reduce, reuse, recycle and renew. Analysis and evidence show that nuclear applications can complement existing technologies and thus accelerate the transition towards a **circular economy for plastics**. However, beyond a group of specialists, the potential contribution of nuclear science and technology to contribute to a solution to the plastics waste problem is not well known, and hence is rarely integrated into proposals for sustainable, scalable solutions. A change is needed to not only make the potential of nuclear techniques and technologies more widely known, but more importantly to apply these more broadly in practice to tap the full potential of nuclear techniques' role in reducing the global plastic waste burden. For this to happen and based on its previous and existing work on this issue, the IAEA has developed NUTEC Plastics to assist the IAEA Member States in integrating nuclear and nuclear derived techniques in their efforts to address challenges of plastic pollution – making IAEA's contribution to solving this global problem more apparent and perceptible.

The IAEA has supported and is continuing to support research and uptake of nuclear techniques in two main areas of activity: monitoring and assessment of marine plastics and plastic/polymer waste recycling and upcycling.

Radiation technology for industrial purposes, such as gamma and electron beams, offers unique characteristics and advantages for reducing plastic and polymer waste and therefore fill existing technological gaps in dealing with waste. Irradiation can address sorting challenges experienced by mainstream mechanical recycling methods by enabling effective sorting of plastic wastes to feed into recycling streams, thus improving the quality and value of the recycled plastics. Radiation technologies can be used to transform or recycle plastic waste into other products, such as fillers and binders for construction materials. They can be used to break down or convert waste plastic polymers into fuel or smaller components to generate chemical feedstocks to produce consumer products, with or without the addition of virgin (e.g. non-recycled) polymers. Reduction of plastic waste is also possible through replacing petroleum-based plastics with biodegradable biopolymers obtained by radiation-driven processes. Furthermore, radiation technology offers cleaner production and recycling processes thus reducing the use of potentially harmful additives and solvents as well as delivering energy savings.

Oceans are the final repository of most unrecycled land-based plastics, and there is a lack of sufficient knowledge and understanding of the abundance and impact of **microplastics in the ocean**. More accurate data are needed to assess the effect that microplastics and associated contaminants have on marine organisms that are part of the global food chain, including as food for people, and therefore on seafood exports, food safety and human health. **Isotopic techniques** offer unparalleled precision and complement conventional techniques in tracking the abundance and distribution of nano- and microplastics in the marine environment. Isotopic tracers, imaging techniques and gamma and beta counters have unique abilities to assess the impacts of micro- and nanoplastics on marine biota. These techniques provide important markers for studying the toxicity of plastics on living organisms, to reveal in detail the impacted organs and systems, and allow to trace the actual toxicological stress and their possible propagation in food chains that can ultimately impact humans through consumption of seafood.

The IAEA maintains and operates **environmental laboratories** in Austria and Monaco. The laboratories have a proven track record of conducting applied research and development (R&D), providing training and analytical services as well as transferring proven nuclear techniques to Member States in the field of environmental monitoring. The IAEA undertakes these R&D activities not only in its own laboratories — which makes the IAEA unique in the United Nations system — but also through its extended research networks, composed of research institutions, academia and reference laboratories around the world. It does so through its Coordinated Research Programme and Collaborating Centres schemes.

Through its **technical cooperation programme** the IAEA supports countries to build capacities and transfer technologies and knowledge in radiation technology and marine monitoring, among others. Currently, there are over 40 ongoing/planned national and regional technical cooperation (TC) projects that relate to radiation technologies and environmental monitoring related to the oceans.

Economic and financial modelling is used to estimate the contribution that technologies, including those based on nuclear solutions, can potentially bring to accelerate the transition to a circular plastic economy. The methodological approach has been applied at two levels: first, a comparative cash-flow analysis estimates efficiency gains of the use of irradiation technologies complementing existing recycling processes (chemical and/or mechanical); second, using the Plastics to Ocean (P2O)[1] model, developed to analyse the stocks and flows of plastic and plastic waste at a global level, a sector-based analysis was performed to assess the potential benefits that the introduction of new technologies generates. This approach estimates the 'value added' that nuclear and nuclear-derived technologies can bring about and provides the rationale for connecting laboratories with plastic recycling technology testing and validation initiatives with the technical cooperation programmes, thus reducing the time-lag of technology transfers and increasing the efficiency and effectiveness of the IAEA's efforts.

NUTEC Plastics will further strengthen and scale-up the development of reliable and cost-effective techniques to assess the spatial and temporal abundance and character of **marine plastics** to better understand their origin, transport mechanisms, as well as fate and impact. This includes the establishment of harmonized, standardized protocols to identify microplastics in environmental samples, analytical techniques that are in line with best practices and state-of-the-art science, and training for scientists and technicians in their use.

NUTEC Plastics will integrate **radiation technologies** for plastic waste recycling into national, regional, and global initiatives. Ongoing laboratory-scale activities are paving the way for pilot plastic recycling plants to establish the volume, energy and financial balances associated with using radiation technologies to recycling various plastic wastes. Based on the proof of principle and experience gained from the pilot(s), the technology will be scaled-up to a large-scale plastic waste recycling demonstration plant(s).

A holistic and sustainable solution to the global plastic burden requires an integrated and comprehensive approach that can only be achieved in **partnership** with organizations with complementary role and expertise. Working within existing national, regional and international initiatives, including private-public partnerships, at both global and country levels is essential. This includes collaboration with United Nations entities, multilateral development banks, philanthropies, existing large-scale partnerships including multi-stakeholder platforms, private sector, and scientific and research institutions. The private sector will be a critically important partner in making the transition to a circular plastic economy, underpinned by strong governmental action and ownership through enabling policies and supportive legal environment. Hence, it is essential for the IAEA to collaborate with existing high-profile **public-private partnerships,** foundations, private sector associations, as well companies producing plastic products and industries that recycle plastic or are major users of these products to test and apply the feasibility and effectiveness of radiation for plastics recycling and up-scale the proposed solutions.

NUTEC Plastics' two main components – monitoring and assessment and plastic recycling — are logically intertwined as both represent a contribution to the solution of the global plastic pollution problem. However, **implementation** of the two components is not contingent on each other. Taking this connected but not co-dependent relationship into account, NUTEC Plastics adopts a **modular approach**. This approach offers the advantage of facilitating the implementation of certain activities according to resource availability, while offering donors and partners the opportunity to engage in specific activities linked to their profile, preferences and priorities. Several plastic related activities are currently being implemented.

NUTEC Plastics is and will be implemented using a variety of **well-established IAEA implementation modalities** such as TC projects, coordinated research projects (CRPs) and other programmatic activities.

1. Strategic Context

1.1. Development challenge

Description of the plastic challenge

Plastic is an indispensable feature of modern life, in fact, it is probably the world's most-used material. Durable by design, inexpensive to produce, in the 150 years since synthetic polymers have been invented and the 70 years since large-scale production began, plastics have transformed our world. Plastics undoubtedly have many benefits: they protect fragile products from damage during transit and from contamination or other damage caused by humidity, microorganisms or light, thereby also improving food safety; plastics preserve products for longer periods of time, thus reducing waste; due to plastics lightweight, it helps save fuel during long distance transport, consequently making transportation more efficient. However, it is the very ubiquity of plastic that has created a rapidly growing global challenge. Scientific data show that the vast quantities of plastics being produced and discarded are harming the ecosystems and natural resources, with grave implications potentially for biodiversity, food safety and human health [2].

Linear economy and the scale and impact of plastic pollution

In 2017, the first global analysis of the production, use and fate of all plastics estimated that over 70% of all plastics ever produced is now waste – 6.3 billion metric tonnes out of a total of 8.3 billion metric tonnes – and that only 9% has ever been recycled [3]. On current trends, the ocean is expected to contain one tonne of plastic for every three tonnes of fish by 2025, and by 2050, there will be more plastic than fish in the marine environment [4]. In many places around the world, plastic waste is mismanaged and ends up in uncontrolled landfills or open dumps, from there much of it enters oceans either through rivers and other waterways or is carried there by wind. Plastic waste however also has implications on land, with soils or groundwater being polluted.

Plastic is by design durable and this longevity means that once it enters the ocean, it can remain there for hundreds of years. Over time it fragments and becomes micro- and nanoplastic, which can enter living organisms and the food chain. Ultimately, plastic does not disappear but accumulates, including in the oceans. It is estimated that since 1950 more than 150 million metric tonnes of plastic have reached the oceans [5].

Plastic pollution is known to particularly affect marine ecosystems and their animals [6]. The possible impact of plastics on human health is the subject of a wide range of studies. Many of these deal with the human intake of microplastics through the food chain, and the possibly harmful effects of plastic through the accumulation of toxic additives. So far, there has not been any direct scientific evidence suggesting that microplastics are directly harmful to human health. Plastic pollution is, however, not only an environmental and human health problem, but it is also a major socioeconomic development challenge which can impact biodiversity, infrastructure, tourism and livelihoods in the fisheries sector.

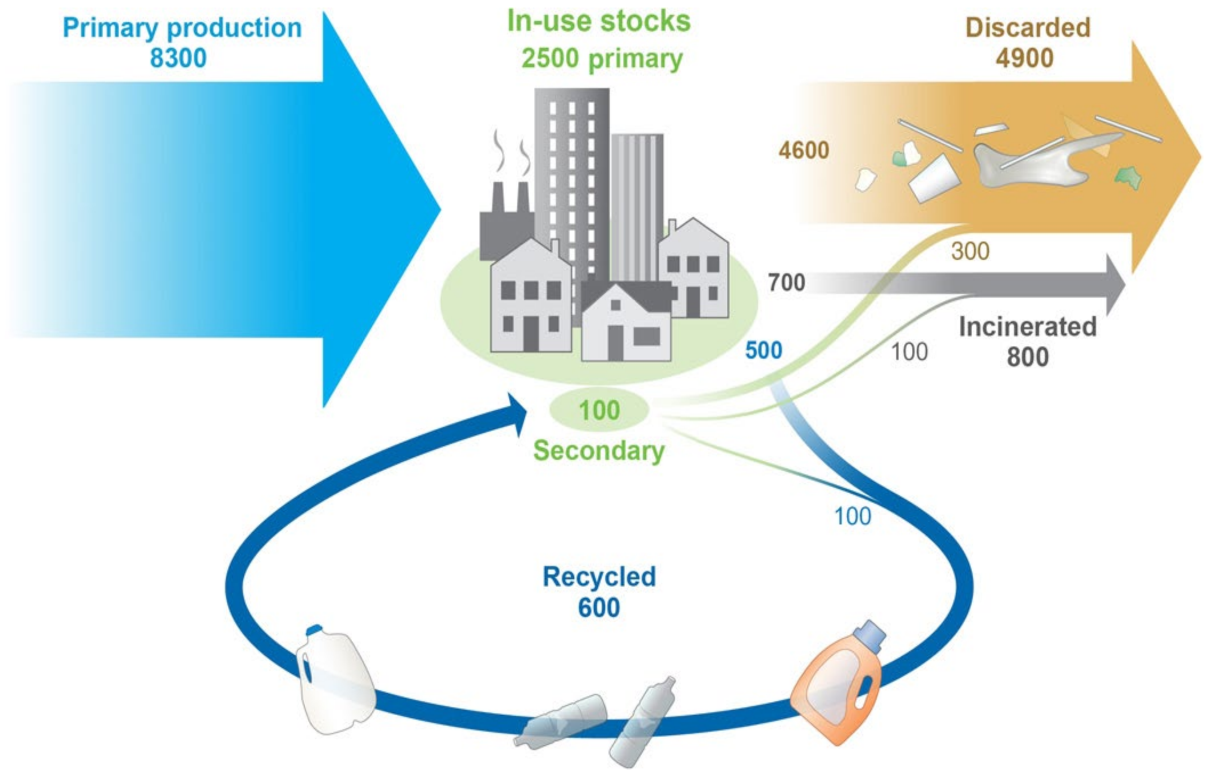

FIG. 1. The overall plastic waste equation: where does plastic end up? (Source: GEYER, R., JAMBECK, J.R., LAW, K.L., Ref [3])

The plastic economy so far has largely followed a linear model of 'take, make and dispose', which discards plastic the moment it is no longer useful for its original purpose. Despite the huge importance of plastics for the global economy, it is obvious that its many benefits are increasingly overshadowed by the detrimental effects and negative externalities that plastic as waste carries with it. As a result, several countries have banned certain types of single use plastics. The COVID-19 pandemic will add to the already existing global plastic waste burden, due to the sharp increase in demand for single-use plastic products such as personal protective equipment, and other single-use plastic items used as a result of hygiene and health considerations.

Differential gender impacts

The extent to which different groups in society are affected by plastic waste pollution – as with other kinds of environmental pollution – differs according to factors such as gender roles and responsibilities, varied economic conditions, access to resources, cultural expectations and differences in knowledge and awareness levels. For example, the effects of marine plastic pollution on women and men in the tourism, fisheries and shipping industry will differ depending on their occupation and participation within these sectors. Therefore, the transition to a circular economy for plastics requires developing an inclusive plastics value chain which takes gender into consideration. Gender-specific roles and attitudes need to be considered when planning effective and appropriate interventions.

Mismanagement of plastic use and plastic waste

The sharp rise in plastic production is driven by multiple factors, such as population and income growth, and the preeminent reason is growth in plastic packaging. Forty-two per cent of all non-fibre plastic is used for packaging materials, which are used for a year or less, on average, before being discarded. Of all plastic produced between 1950 and 2015, only 9% has been recycled, while 12% has been incinerated and 60% has been discarded in landfills or the environment, with the remainder in stock/in use [3]. (see Fig. 1.)

These figures present an overall global picture over a period of six and a half decades. Nevertheless, it is also clear that plastic waste management, and plastic recycling specifically, shows variations by region and over time. For instance, plastic recycling rates in many high-income countries have continued to increase steadily since the early 2000s and have in some cases crossed the 30% mark whereas many poorer countries have barely reached plastic recycling rates of 10% [7]. For low- and middle-income countries, plastic recycling rates are not well known, but can be expected to be significant at least where an efficient informal plastic waste management system exists [8].

For land-based sources of plastic pollution, improved solid waste management systems at the disposal, collection and recycling stages of product lifecycles are fundamental to solving the problem, particularly in low- and middle-income countries. According to the United Nations Environment Programme (UNEP), the average waste collection coverage in low-income countries reaches only 36%, in lower-middle income countries 64%, in upper-middle income countries 82% and in high-income countries almost 100% [9]. Having reliable and comprehensive waste management systems and infrastructure coupled with regulations that encourage recycling are key factors for attaining high rates of plastic recycling.

Thus, what happens to plastic after it has been used very much varies from one country to the other, depending on the waste management system in place. Consequently, if not adequately disposed of either through recycling, incineration or orderly landfill, much of plastic waste sooner or later ends up in the environment. Without any action taken, the amount of plastic waste entering the oceans could nearly triple by 2040. Even if current existing government and industry commitments to reduce the flow of plastic pollution were fully implemented, this would only lead to an annual reduction of plastic leakage into the ocean by close to 7% [10].

There are many reasons why only 9% of all plastic produced to date has been recycled and one of the most crucial is linked to the costs of transitioning from a linear plastic economy to a circular one, in which discarded plastic is not considered as garbage but as a valuable resource and raw material. Such a change requires high up-front investment costs and requires a more favourable enabling environment [11]. For instance, plastic waste recycling is much more complex than traditional waste management and processing, as it requires separate collection and sorting leading to higher overall costs than recycling systems for other materials such as glass or paper. Other inhibiting factors explaining low rates of plastic recycling are linked to the material features of some types of plastics, which for instance can be particularly thin, e.g. bags or films, or have multiple layers of different types of polymers, and are therefore particularly difficult and/or expensive to recycle. Low recycling rates for plastic packaging represent an enormous economic loss: an estimated US $80 to 120 billion worth of material value is lost annually [12].

1.2. Results of international efforts to date

It is evident that the linear model of plastic production, use and disposal is not sustainable. Rather, a different approach is needed, as manifested by the initiatives of various organizations, and in this line, NUTEC Plastics works towards establishing a circular economy for plastic and focusing on the ‘4Rs’: reduce, reuse, recycle, and renew. Elements of the ‘4Rs’ concept include economic incentives for the reuse and recycling of plastics, curbing the leakage of mismanaged plastics waste into the environment, and detaching the production of plastic from fossil feedstocks by using alternative, renewable feedstocks. This requires ambitious efforts of a multitude of actors making the best use of all technologies available.

Plastic pollution has become an issue of global environmental concern and has attracted attention not only from the scientific community but also governments [13]. And indeed, countries around the world have already begun to take action through the adoption of national policies and programmes to reduce plastic waste and increase plastic recycling. These efforts have been matched by a multiplicity of regional and global initiatives on plastic waste. Like other global environmental problems, addressing plastic waste pollution requires cooperation from a broad set of actors at international, regional, national and local levels. Ultimately, however, it is governments that are the main drivers for addressing the problem given their responsibility for regulating political, social and economic matters both domestically and vis-à-vis other states.

The policy and regulatory environment is a decisive factor in determining the success of efforts to curb plastic waste pollution by incentivizing a reduction in the use of virgin plastic, increasing recycling quotas and augmenting the demand for recycled plastic. Even if current government and industry commitments where to be fully met, by 2040 the likely reduction in annual plastic leakage to the ocean will only be 7% (±1%), compared to a business-as-usual scenario [10]. What is needed is a system change towards a circular economy for plastic, in which the amount of mismanaged or disposed plastic is drastically reduced by curbing demand for plastic through substitution with alternative materials and increased recycling rates. For this to happen, the right incentives need to be in place, further innovation needed, and capital investment required.

Achievements and gaps in policy and regulatory frameworks

According to the Plastics Policy Inventory[1], some 322 policy instruments have been adopted between the year 2000 and mid 2019 with the explicit aim of addressing plastic pollution; of these instruments, 29 were international, 43 regional, 151 national and 99 subnational [14]. These policy instruments have been regulatory, economic or informative in character referring to different modalities used for addressing plastic pollution, for instance developing plastic reduction plans, developing new or improving existing production processes, limiting the use of plastic, banning products, recycling quotas, subsidies, cash for return schemes, taxes, etc.

International instruments and initiatives

The instruments adopted at the international level are predominantly legally non-binding. Over time, these instruments have become more complex and specific in scope, specifically targeting plastic pollution. Instruments have rather focused on voluntary monitoring and on calling upon states to develop and implement national action plans. The recommendations set forth internationally mostly include affirmative regulatory actions regarding plastic waste management and clean-up; education and outreach campaigns; economic incentives for improving plastic waste management; and economic disincentives on single-use plastic.

Action against plastic waste pollution on the international level goes beyond adopting certain instruments. Among these initiatives, the Alliance to End Plastic Waste, the New Plastics Economy Global Commitment of the Ellen Macarthur Foundation in collaboration with UNEP, the Global Plastic Action Partnership (GPAP) hosted by the World Economic Forum, the Ocean Plastic Charter of the G7, or the G20 Implementation Framework for Actions on Marine Plastic Litter of the G20 are some examples. The United Nations has proclaimed a Decade of Ocean Science for Sustainable Development (2021–2030) to support efforts to reverse the cycle of decline in ocean health and gather ocean stakeholders worldwide behind a common framework [15].

Most of these initiatives operate in several countries, and the majority are led by intergovernmental organizations such as United Nations bodies, convention secretariats, regional and coordinating centres (e.g. UNEP, the World Bank or OECD), followed by non-governmental organizations, and business and industry. Almost half of the initiatives are multi-stakeholder, often with business and non-profit organizations working jointly on the transition towards a circular economy for plastic.[2]

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[1] See DUKE UNIVERSITY, Plastics Policy Inventory (2020), https://nicholasinstitute.duke.edu/plastics-policy-inventory.

[2] The Ellen MacArthur Foundation, in collaboration with UNEP launched in 2018 the New Plastics Economy Global Commitment, with more than 500 organisations setting targets to address plastic waste and pollution at its source, by 2025. See https://www.newplasticseconomy.org/assets/doc/npec-vision.pdf

Regional instruments and initiatives

Regionally, an increasing number of policies and instruments are being adopted. Similar to the international level, regional policies on plastic pollution have become more targeted over time, focussing on specific types of plastic pollution [14].

In 2018, the European Union (EU) adopted its Strategy for Plastics in a Circular Economy, which aims at transforming the way plastic products are designed, used, produced and recycled [16]. According to this Strategy, by 2030, all plastic packaging placed on the EU market has to be either reusable or recyclable; more than half of plastic waste generated in the EU has to be recycled; and sorting and recycling capacity has to have increased fourfold from 2015 levels. In Asia, the Association of Southeast Asian Nations (ASEAN) adopted in 2019 the Bangkok Declaration on Combating Marine Debris in the ASEAN Region, in which members declared their intention to step-up efforts to prevent and reduce marine plastic pollution in an integrated land-to-sea approach, to strengthen laws and regulations, to promote innovative solutions towards a circular plastic economy and to enhance regional and international cooperation and information sharing [17]. Another initiative is the United Nations Economic and Social Commission for Asia and the Pacific (ESCAP) Closing the Loop project, which is geared at detecting and monitoring the sources and pathways of plastic waste entering rivers [18]. In Africa, the African Marine Waste Network project is an initiative that works on creating knowledge on plastic pollution, awareness-raising and education [19]. In Latin America and the Caribbean, the multisectoral Regional Initiative for Inclusive Recycling, led by Inter-American Development Bank (IDB), is focusing on formal and informal recycling sectors [20].

National and subnational instruments and initiatives

Most instruments have so far been adopted at national and subnational levels, and largely in high- and upper-middle income countries [14]. Affirmative regulatory action includes the development of plans, improvements of existing processes and products or incentives for responsible handling of plastic. Prohibitive regulatory actions include limitations or banning of plastic, or the prohibition of irresponsible handling of plastic. Subsidies, tax breaks, cash for return schemes and disincentives such as fees, taxes, levies or duties are used as additional economic modalities. Finally, states make use of information campaigns through education and outreach, labelling of plastic, and research, data collection and reporting.

2. The Comparative Advantage of Nuclear Technologies

2.1. Nuclear technology in the context of circular plastic economy

There is global recognition that plastic pollution requires a long-term, sustainable and economically feasible solution that moves away from the linear ‘take-make-waste’ model.[3] Tackling this challenge depends on the swift transition to a circular plastic economy – factoring in the technical and economic feasibility – built on the 4R principles: reduce, reuse, recycle, renew.

Although the problem of plastic pollution has achieved significant international visibility, the global response has largely been ad hoc to date. Gaps in addressing plastic pollution are a major impediment, including lack of sufficient awareness, knowledge, technologies, financing and policy [21]. The application of tailored

[3] Relevant UNEA-4 resolutions include Resolution 4/6 on addressing marine plastic litter and microplastics (UNEP/EA.4/RES.6), Resolution 4/9 on addressing single-use plastic products pollution (UNEP/EA.4/ RES.9), Resolution 4/11 on protection of the marine environment from land-based activities (UNEP/EA.4/RES.11) and Resolution 4/1 on innovative pathways to achieve sustainable consumption and production (UNEP/EA.4/RES.1). are available at: https://web.unep.org/environmentassembly/proceedings-report-ministerial-declarationresolutions-and-decisions.

nuclear and nuclear-derived techniques offers unique science-based solutions for monitoring marine microplastic pollution and its ecosystems impacts, as well as for improving recycling of plastic waste.

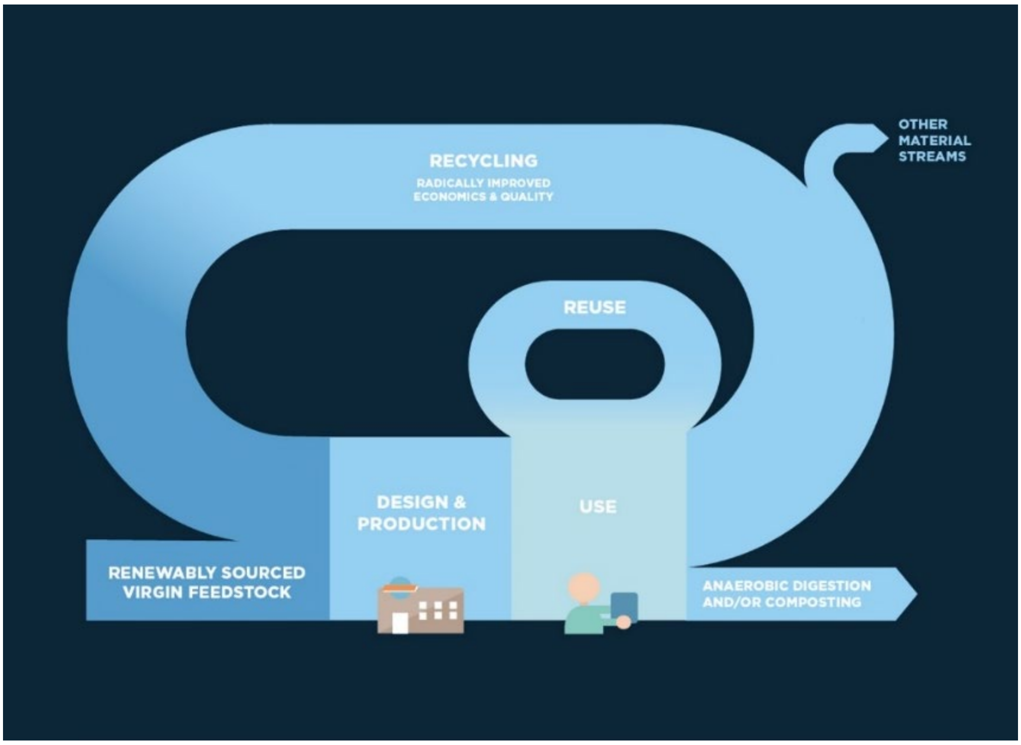

FIG. 2. The circular plastic economy.(Source: ELLEN MacARTHUR FOUNDATION[4])

Current conventional recycling technologies

The only sustainable management option for plastic waste is through comprehensive recycling – the process of converting plastic waste into new plastic products. There are two main recycling techniques that are currently used: mechanical and chemical recycling. Plastic waste that is not compatible with the current mainstream recycling technologies can be incinerated as a fuel source, a process known as energy recovery, re-manufactured or upcycled into new value products (fuel and additives).

Mechanical recycling is to date the most common method for recycling plastic waste [22]. It recovers mostly homogeneous waste plastics, producing raw material that can be looped back into plastics production, thus substituting virgin plastics. This process typically includes collection, sorting, washing and grinding of the material to create plastic pellets that are later melted and re-processed for the production of new plastic-based products [23]. Only thermoplastics can be recovered this way (materials that can be re-melted and re-processed into products). These make up around 12% of global plastic production [24].

Although a relatively cheap industrial process, mechanical recycling of plastics has some limitations. It requires the sorting of different polymers, which is for multiple-layer or mixed plastics a particular challenge. Furthermore, the quality of the recycled material degrades in each cycle and, as a result, mechanical processing cannot be used for more than one or two rounds of recycling.

Unlike mechanical recycling, chemical recycling can process mixed streams of plastic waste. Chemical recycling refers to a variety of technologies – for example gasification, pyrolysis, fluid-catalysed cracking

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[4] See: ELLEN MacARTHUR FOUNDATION, A Circular Economy for Plastic (2016), www.ellenmacarthurfoundation.org/assets/images/Deep-Dives/m4_circular_economy_for_plastics_big_image_2000px.jpg.

and hydrocracking – that depolymerise plastic to its molecular level and transform plastic waste into secondary raw material or fuel.

Chemical recycling has an advantage over mechanical recycling in that it can be used to process wider streams of plastics including those that are mixed, contaminated or of low quality. Critically, however, chemical recycling may lead to the release of toxic additives and contaminants, some of which are already banned by national regulations in various jurisdictions. As a result of these problems and the associated costs, commercial chemical recycling operations are still rare.

Nuclear technologies in the plastics circular value chain

Radiation technology, and specifically gamma and electron beams, offer unique advantages to address the technological gaps that exist in plastic recycling. These technologies can complement conventional technologies. The latest research shows that radiation-supported recycling offers advantages including improved process control, enhanced quality of recycled plastics and the ability to tailor the properties of products, as well as significant cost and energy savings. The advantages of the technique rest on the ability to control how chemical bonds in plastic polymers are formed or broken, thereby allowing the special properties of the polymers to be altered, creating new chemical compositions or breaking them down.

Radiation technologies can break down plastic polymers into smaller fragments of chain molecules that can be used as feedstocks to produce new consumer products, with or without the incorporation of virgin polymers. Radiation can also be used to modify the properties of waste polymers, for example, to obtain novel materials which can then be used to make new products. Irradiation, specifically low electron beam, can also be used to increase and improve recycling by enhancing the sorting of mixed plastics, as a result of electrostatic separation. Radiation processing also allows the properties of polymer waste to be tailored, creating new composites and enabling innovative repurposing of waste materials. This helps to keep plastic repeatedly usable, further reducing plastic waste.

Radiation technologies can be used for irradiating even large volumes of polymer wastes. This has implications for the commercial utility and application of the technology. Also, radiation technologies can be used to recycle waste plastics into new products when other methods are no longer feasible. This has the potential to reduce the volume of virgin fossil-fuel plastics from entering the plastics value chain, yielding a further environmental benefit.

Irradiation to improve chemical recycling processes

By combining irradiation with pyrolysis – changing the chemical composition of materials using heat – to generate new chemical feedstocks or fuel, irradiation offers cleaner production processes for chemical recycling by avoiding solvents and catalyst additives. It also has the potential to improve the energy efficiency of the process and to boost the quality and yield of the end-product.

2.2. Marine plastic pollution

The ocean is the final repository for much of land-based plastic pollution [25]. Millions of tonnes of plastic litter enter the marine environment annually, and these quantities are expected to increase in the coming years [26]. Due to their size, plastic particles can be both actively and passively ingested by many marine species, including those relevant to global fisheries. The full scale of marine plastic litter has not yet been systematically or fully accounted for [27].

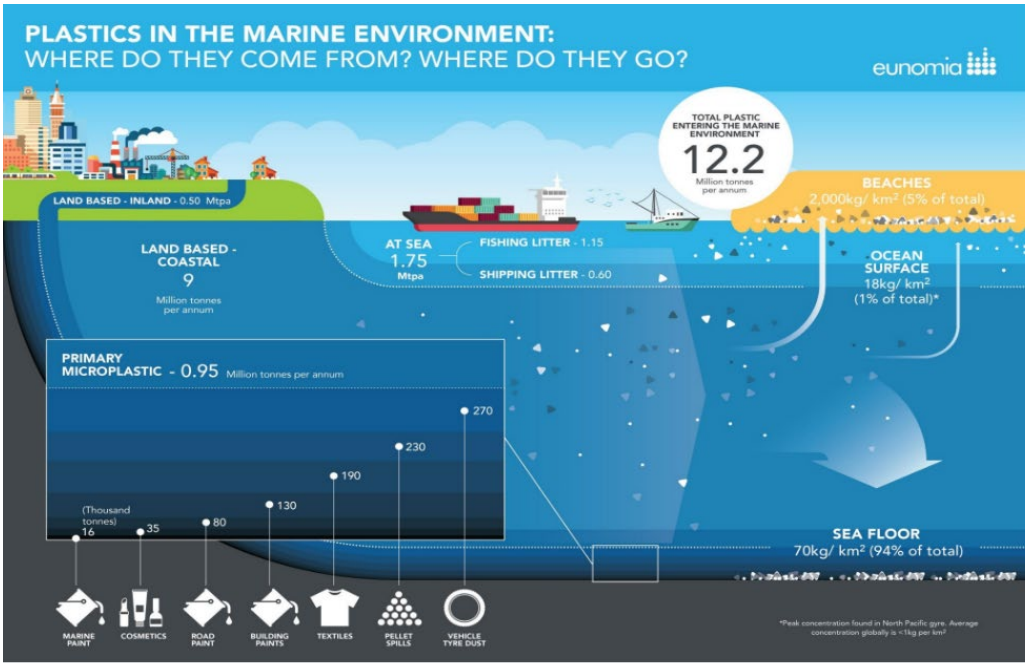

FIG. 3. Plastics in the marine environment: Where do they come from? Where do they go? (Source: ECOWATCH[5])

The implications of plastic pollution on marine life and more broadly on coastal and open ocean ecosystems are still uncertain and need careful monitoring and assessment [28, 29]. Indeed, recent assessments point to concerning initial findings of accumulation of microplastics even in the human gastro-intestinal tract, which may yield deleterious effects [30, 31].

Given the many uncertainties surrounding marine plastic waste, it is essential to increase understanding of the scale and impact of marine plastic pollution on coastal and marine ecosystems and organisms [3]. Over the last decade, the global scientific community has invested considerable effort into advancing knowledge of the abundance and impact of selected plastic particles on aquatic organisms [27]. It has also been observed that plastics in the ocean are dispersed effectively throughout the water by currents and tides and undergo continuous physical and chemical degradation leading to smaller and smaller plastic particles. This degradation process can also release co-contaminants that are either inherent to the composition of the plastic particle or scavenged by reactive particle surfaces [29]. Much more data is needed for a full understanding of the effects of these co-contaminants on marine organisms and for strengthening food safety and security, including seafood exports on which the livelihoods of coastal populations in many countries depend.

Advantages of nuclear and derived techniques

Specialized isotopic techniques offer unparalleled precision and utility and can complement other techniques in tracking the spatial and temporal abundance, as well as the character and impact of marine plastic particles. As such, they contribute to comprehensive monitoring and assessment of marine litter, the development of mitigation strategies at the policy level, as well as for evaluating the effectiveness of such measures.

Isotopic tracers and nuclear imaging techniques offer several advantages in assessing the impact and stress caused by plastic in the marine environment: i) they are analytically sensitive, allowing for more precise and therefore reliable projections; ii) cross contamination of samples is typically much less of an

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[5] See: ECOWATCH, 80% of Ocean Plastic Comes From Land-Based Sources, New Report Finds (2016), www.ecowatch.com/80-of-ocean-plastic-comes-from-land-based-sources-new-report-finds-1891173457.html.

issue compared to working with organic or inorganic contaminants, which facilitates broad interlaboratory exchange; iii) they permit non-destructive analyses, which allow for experimental work on live organisms and iv) they provide an overview of the effects and movement of contaminants on and within the whole organism. This provides an important marker for the potential toxicity of plastics on living organisms and reveals in great detail the impacted organs and systems, which in turn allows the tracing of actual toxicological stress and possible propagation in food chains that can ultimately affect humans through our consumption of seafood.

In addition, nuclear techniques can also help identify the added environmental impact of plastics as they degrade and release and scavenge co-contaminants, such as PCBs (polychlorinated biphenyls) and halogenated flame retardants as well as trace elements such as mercury and lead. Estimating the pathways and impacts of such processes is increasingly important as the amount of plastics in the ocean grows and oceans are subject to increased warming because of climate change.

2.3. The IAEA's role and approach

According to its Statute,[6] the IAEA is mandated to accelerate and enlarge the contribution of nuclear science and technology for peaceful uses. As such, the IAEA is a hub for the development and transfer of nuclear technologies and applications. Nuclear technologies undergo rigorous research and validation through IAEA's research activities. Once relevant nuclear technologies are mature enough, these can then be transferred to all countries, especially developing Member States through IAEA's technical cooperation programme.

The IAEA has a long and successful history of supporting research and development of nuclear and nuclear-derived technologies' applications. The IAEA, through its Department of Nuclear Sciences and Applications (NA) maintains and operates environmental laboratories in Austria and in Monaco.7 The laboratories support and implement activities that respond to the developmental needs of Member States in a range of subject areas. They have a well-established track record of conducting applied research and development, providing training and analytical services as well as transferring proven nuclear technologies and techniques to Member States.

The IAEA undertakes research and development activities not only in its own laboratories, but also through its extended research networks, composed of research institutions, academia and reference laboratories. It does so through its Coordinated Research Programme and Collaborating Centres[8] schemes.

A number of Collaborating Centres are of direct relevance to NUTEC Plastics. Whereas some partner institutions have a particular expertise in radiation processing of polymers, waste polymers and biocomposites, others have their research focus on marine and oceanographic studies, including marine environment pollution. The potential benefits from NUTEC Plastics are enhanced for regions and countries that have these IAEA Collaborating Centre designations in place.

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[6] Article III A of the Statute states that the IAEA is authorized "to encourage and assist research on, and development and practical application of, atomic energy for peaceful uses throughout the world; and, if requested to do so, to act as an intermediary for the purposes of securing the performance of services or the supplying of materials, equipment, or facilities by one member of the Agency for another; and to perform any operation or service useful in research on, or development or practical application of, atomic energy for peaceful purposes."

[7] The Nuclear Science and Instrumentation Laboratory develops, adapts and transfers nuclear instrumentation as well as accelerator applications to Member States for a wide range of operations from environmental monitoring to materials science. The three IAEA marine environment laboratories in Monaco are dedicated to the understanding and preservation of a healthy marine environment and the sustainable development of environmental resources.

[8] For more background on Collaborating Centres, see: https://www.iaea.org/sites/default/files/16/07/iaea_collaborating_centres_scheme_external_guide_v1.1_april_2016.pdf.

Experiments are conducted on a daily basis at the IAEA Environment Laboratories.

Beyond its Collaborating Centre scheme and the work in its laboratories, the IAEA also encourages and assists research, development, and the practical use of nuclear technologies and applications in Member States throughout the world. It brings together research institutions from its developing and developed Member States to collaborate on research projects of common interest in so-called coordinated research projects (CRPs). Through these CRPs, the IAEA, as coordinating body, awards research, technical and doctoral contracts and research agreements to institutes in Member States.

The IAEA has a proven track record in supporting the research, development, and uptake of specific nuclear techniques in the context of the plastics value chain. The IAEA applies nuclear science and technology to complement existing conventional techniques and bring new solutions to help its Member States.

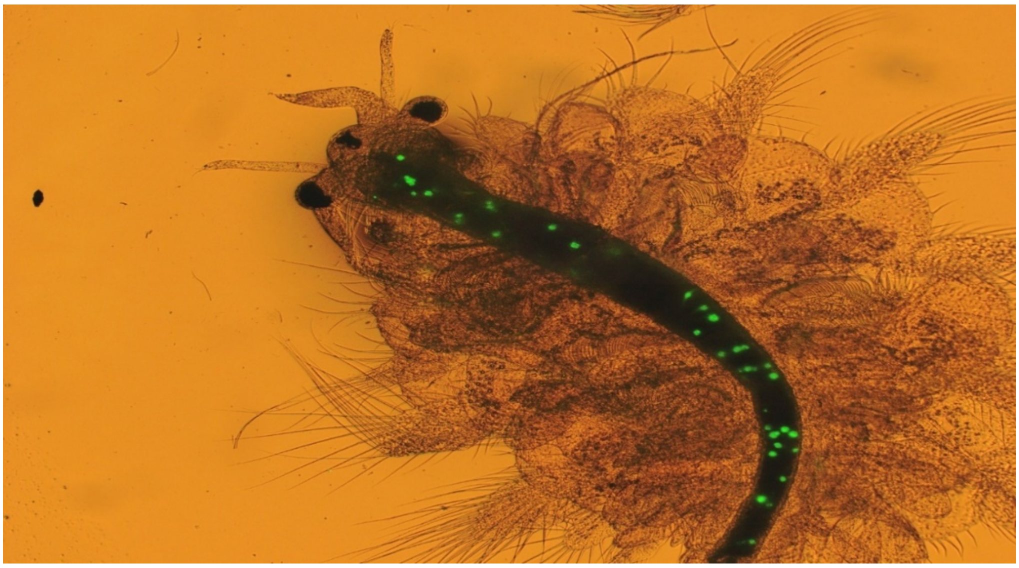
Under NUTEC Plastics, the IAEA Environmental Laboratories will further strengthen and scale-up the development of reliable and cost-effective techniques to assess the spatial and temporal abundance and character of marine plastics in order to better understand their origin, transport mechanisms, and fate and impacts. This includes the establishment of harmonized, standardised protocols to identify microplastics in environmental samples, the training of scientists and technicians, and establishment of analytical techniques that are in line with best practices and state-of-the-art science. Concurrently, comparative monitoring of microplastics can help quantify and identify the environmental impact of the demonstrator plant.

Marine monitoring

Using nuclear and derived techniques, the IAEA supports Member States working towards the achievement of their national UN Sustainable Development Goals (SDGs) and targets, as well as within the framework of the UN Decade of Ocean Science for Sustainable Development. This work encompasses climate change and anthropogenic impacts on oceans such as land-based or marine pollution, ocean warming, ocean acidification, and ocean deoxygenation. Since 2016, the IAEA Environment Laboratories have been studying the impact of plastics on marine organisms. Findings from these studies are used by governments as science-based information for making policy decisions.

Radiotracer techniques are used by the IAEA to study the fate of contaminants or biotoxins in coastal environments, as well as the influence of global stressors such as climate change on marine organisms. These tools are now important in examining the effect of plastic on aquatic life.

Through IAEA's technical cooperation programme, many countries are enhancing their knowledge in monitoring and mitigation of different pollutants, such as assessing radionuclides and non-radioactive contaminants and their effects on the environment and ecosystems. The IAEA is the world's largest supplier of reference materials for radionuclides in different matrices, such as fish, plants, soil, water or other matter, some of which function as international measurement standards, and provides these to laboratories worldwide to help them ensure that proper nuclear and non-nuclear analytical techniques are applied to achieve accurate, trustworthy and reliable results.



Close-up of an Artemia brine shrimp after having consumed microplastic particles at the IAEA Environmental Laboratories. (Photo: F. Oberhaensli/IAEA)

Capacities already built by the TC programme in sampling marine pollution, control of algal blooms, analysis of contaminants (including heavy metals, organic compounds, radioactivity and toxins), seafood safety, as well as laboratory experiments using radiotracers provide a strong foundation for the implementation of microplastics monitoring and assessment activities. Existing capacities in these areas could be scaled up to accommodate the characterization and evaluation of plastics pollution through additional state-of-the-art technology (e.g., micro-FTIR, RAMAN, GC-MS and others), as well as specialized trainings.

Radiation of polymers

In the 1980s and 1990s, basic research on the radiation of polymers was already underway through CRPs, with a specific focus on polymers for biomedical and biochemical applications, polymers for industrial and medical use, or radiation processing of indigenous natural polymers.[9] In the 2000s, research and development on radiation technology for polymers continued,[10] and also included radiation-induced grafting for developing novel adsorbents and membranes.[11] Another CRP focused on developing radiation-processed products using natural polymers to generate value-added and marketable products for use in

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[9] These were: CRP385 'Radiation modified polymers for biomedical and biochemical applications' (1980-1983); CRP927 'Radiation modification of polymers for industrial and medical use' (1984-1989); CRP1018 'Stability and stabilization of polymers under irradiation' (1993-1997); and CRP931 'Radiation processing of indigenous natural polymers' (1997-2000).
[10] CRP565 'Controlling of degradation effects in radiation processing of polymers' (2003-2006).
[11] CRP1434 'Development of Novel Adsorbents and Membranes by Radiation-Induced Grafting for Selective Separation Purposes' (2007-2011).

agriculture, healthcare, industry and environment.[12] Other radiation technology CRPs involved the generation of nanocomposites; new scratch and abrasion resistant coating formulations using radiation; radiation-initiated polymerization for coatings with enhanced surface finishing;[13] and the development of new natural and synthetic polymers packaging materials using radiation techniques and assessing radiation effects on food packaging materials.[14] Numerous CRPs have addressed other industrial applications of radiation technologies,[15] many of which have led to successful technology transfer and the emergence of sustainable industries, which demonstrates the track record of the Agency and its partners in such efforts.

A new CRP (approved in 2020) on 'Recycling of Polymer Waste for Structural and Non-Structural Materials by using Ionizing Radiation' is well positioned to form the research and development backbone of the NUTEC Plastics' recycling component. At the end of 2020, a consultation meeting, involving experts in the field as well as counterparts from around the world, provided a clear overview of the technologies being tested as well as recommendations on the best way forward. Many technologies are under different stages of research and testing.

The recommendations from the consultation meeting to the IAEA highlight the importance of NUTEC Plastic's recycling component. The potential of radiation technology for converting polymer wastes into feedstock and new materials for high-performance structural and non-structural applications is well-established and as such the IAEA has received calls from Member States for increased adoption, promotion and technology transfer. Specifically, the IAEA is recommended to analyse and promote the use of in-line and modular radiation processing technologies complementing existing mechanical and chemical processes as an example of scalable manufacturing methods for cost-effective and eco-friendly sustainable solutions in plastic production and recycling. To this end, the IAEA is working to help establish international cooperation at the governmental, industrial, and scientific levels, as well as to increase visibility, presence and global awareness about the usefulness of the safe and secure applications of radiation technologies for recycling polymer waste.

The results of the IAEA's research and development activities are transferred in the form of established knowledge and proven technology to its Member States. The IAEA technical cooperation programme has already built national capacities and enhanced the technical capabilities of Member States for the use of radiation technology for polymer recycling. Many Member States have already benefitted from the transfer of technologies such as electron beams and gamma irradiators for material processing and for creating advanced materials.

3. NUTEC Plastics' Results-Based Approach

3.1. How will NUTEC support a shift towards a circular economy: Theory of Change

From linear to circular

The Agenda 2030 makes a commitment to eradicate multidimensional poverty and achieve sustainable, equitable development for all. The use of nuclear technologies to support a shift from a linear to a circular

[12] CRP1467 'Development of Radiation-Processed Products of Natural Polymers for Application in Agriculture, Healthcare, Industry and Environment' (2007-2013).
[13] CRP1783 'Radiation Curing of Composites for Enhancing their Features and Utility in Health Care and Industry' (2011-2015)
[14] CRP1947 'Application of Radiation Technology in the Development of Advanced Packaging Materials for Food Products' (2013-2017).
[15] CRP1539 'Radiation Treatment of Wastewater for Reuse with Particular Focus on Wastewaters Containing Organic Pollutants' (2010-2016); CRP2220 'Radiation Inactivation of Bio-hazards Using High Powered Electron Beam Accelerators' (2018-2022); CRP2216 'Radiation based technologies for treatment of emerging organic pollutants' (2019-2023).

plastics economy is an inherent contribution to the Agenda 2030. Goal 12 undertakes a commitment by the international community to the sustainable consumption and production patterns and SDG 12.5 specifically calls on countries to "...substantially reduce waste generation through prevention, reduction, recycling and reuse" by 2030.

Addressing the root causes of plastic pollution requires systemic solutions that reduce the demand for finite fossil fuel materials and scale back negative externalities associated with the current plastics value chain. In short, the global community must reduce the amount of plastic entering the economy from virgin feedstock and exiting the economy with no more value added. In other words, the world needs to shift from a waste management approach to a resource management one. This can be achieved by transitioning from a linear 'take-make-dispose' model to a circular economy. Under this model, actions can be taken at multiple stages of the value chain as shown below.

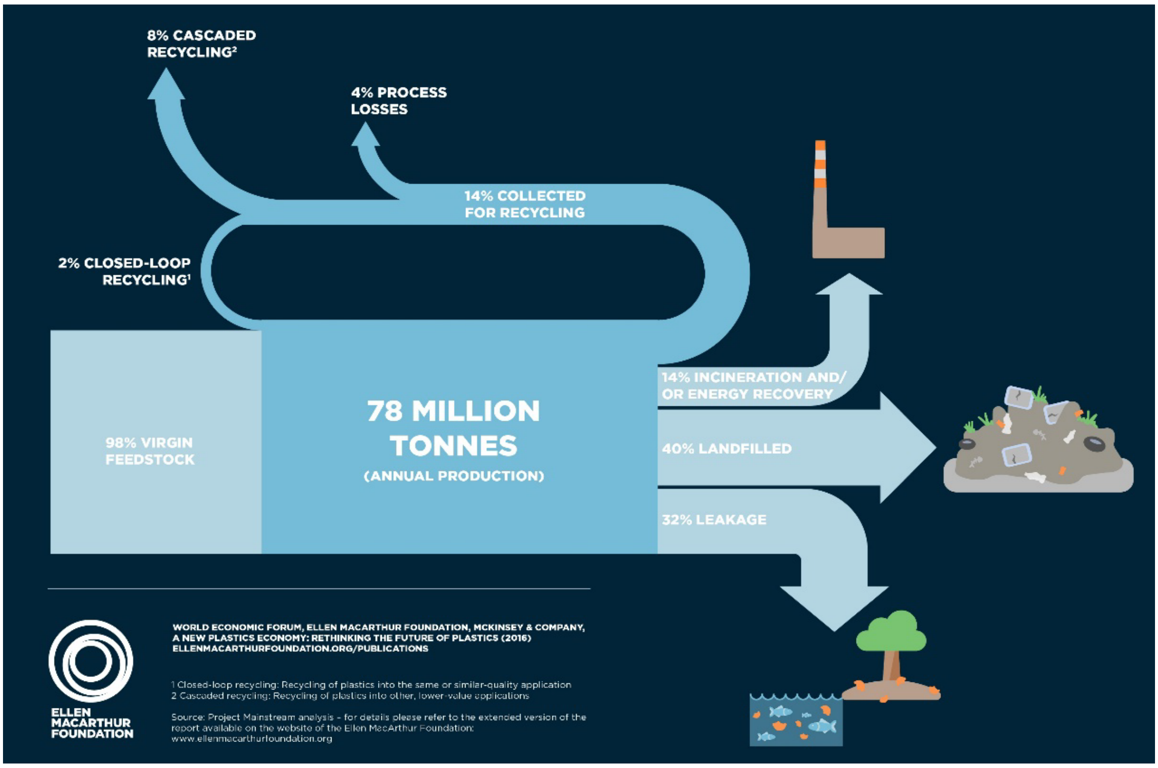
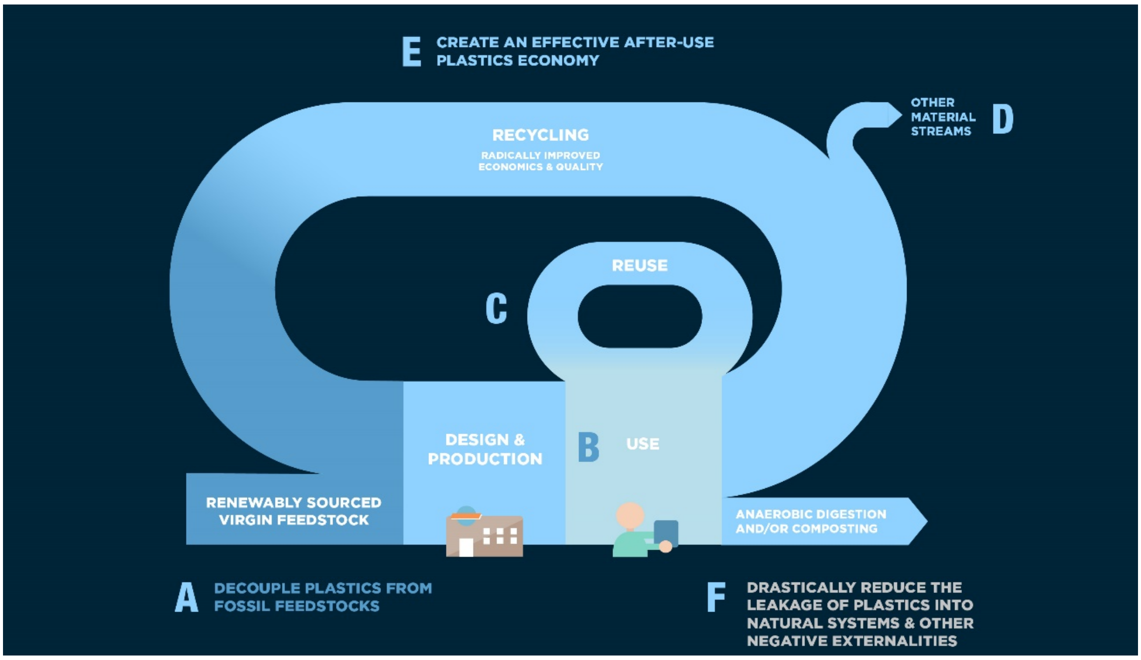


FIG. 4. Global flows of plastic packaging (2013). (Source: ELLEN MacARTHUR FOUNDATION)

The Plastic to Ocean (P2O) [1] model is the 'first of a kind model' which has been developed to analyse stocks and flows of plastic and plastic waste in and through society at a global level. The P2O model allows projections and global analyses to be carried out on all components of the plastic waste management system. NUTEC Plastics is using this model to assess the economic impact of nuclear technologies on the plastic waste economy. Presently, model input parameters are based on predictions and estimates. Once pilot plants are in operation and providing key performance data, the reliability of P2O projections should increase.



A. **Reduce plastic production**
B. **Reduce plastic use**
C. **Increase re-use of plastic products (to avoid single/used and exponential increase of plastic waste)**
D. **Increased recycle of plastic waste into other products**
E. **Increased quality of recycled waste to be used as inputs in plastic production / replacing oil-based inputs**
F. **Clean up oceans and land from existing plastic waste**

FIG. 5. Objectives of the New Plastic Economy. (Source: WORLD ECONOMIC FORUM, ELLEN MacARTHUR FOUNDATION, McKINSEY CENTER FOR BUSINESS AND ENVIRONMENT, Ref. [4])

3.2. Objective and outcomes

The overall objective of NUTEC Plastics is ***to assist the IAEA Member States in integrating nuclear techniques in their efforts to address challenges of plastic pollution.***

The two main outcomes are:

1. Enhanced global understanding of the abundance and impact of marine plastic pollution.
2. Improved recycling and production methods through the application of radiation techniques to complement conventional practices.

Enhanced global understanding of the abundance and impact of marine plastic pollution

This component aims to enable Member States to improve marine plastic management through assessing their baseline situation and projected scenarios regarding plastic pollution in and near their territorial waters. NUTEC Plastics will build the capacity of laboratories around the world to deploy isotopic techniques, alongside others, to monitor and assess the impact of marine plastic pollution, and to enable the exchange of data, knowledge and best practices in this area. Several Member States from all geographical regions have already established strong capacities in marine environmental monitoring with the help of the IAEA and could further benefit from NUTEC Plastics.

Output 1.1: Global awareness raised on the application of isotopic techniques for marine plastic monitoring and impact assessment.

This output aims at building global awareness of the advantages of isotopic techniques in terms of accuracy and precision in order to fill the global knowledge gap in monitoring and impact assessment of marine micro- and nanoplastics.

Output 1.2: Identification of public and private partners to support improved monitoring capacities of marine laboratories.

This output aims to leverage the necessary multi-stakeholder partnerships to facilitate the wider utilization of isotopic techniques for the accurate monitoring and impact assessment of micro- and nanoplastics in the marine environment.

Output 1.3: Operational laboratories with adequate equipment and trained staff established and appropriate protocols adopted.

This output focuses on the transfer of equipment, technical advisory services and trainings, as well as supporting countries in developing protocols for the adequate collection, mapping and tracing of microplastic in the oceans and assessment of their impact on marine ecosystems.

Output 1.4: NUTEC Plastics Monitoring Network.

This output will establish a global network of laboratories capable of monitoring and assessing the impact of marine plastic to enable exchange of data, knowledge and best practices. These laboratories will serve as regional resource centres for continuous provision of services and learning.

Output 1.5: Knowledge about sources, distribution, transport, effects and destination of nano- and microplastics.

This output will advance the research and knowledge on nano- and microplastics.

Improved recycling and production methods through the application of radiation techniques

Radiation treatment is a proven technique in scientific laboratories and has the potential to complement mechanic and chemical recycling. However, it is not well known or included as an alternative solution by the global plastic community. This component aims to provide stakeholders with evidence of the effectiveness and efficiency of radiation techniques in improving existing recycling methods. It will also accelerate the process of transferring technologies from laboratories to commercial use by involving private actors in the validation process and building up partnerships to support early adoption.

Radiation technology is a complementary technique to existing chemical and mechanical recycling process, as such, countries interested in implementing activities under this component need to ensure a set of plastics value chain preconditions as well as enabling regulatory frameworks are in place.

Output 2.1: Global awareness raised on the comparative advantage of irradiation technology in plastic processing and recycling.

This output aims at increasing visibility of irradiation techniques as part of the solution to the plastic pollution problem by building awareness in the global plastic community.

Output 2.2: Identification of public and private partners to support irradiation technology transfers from the lab to the plant.

This output aims to leverage the necessary multi-stakeholder partnerships to facilitate the wider utilization of irradiation techniques in complementing existing plastic production and recycling processes.

Output 2.3: Phase 1: Pilot irradiation machines in recycling plants installed.

This output focuses on ensuring institutional capacities in place are adequate to develop pilot programmes on irradiation technologies for plastic waste management. It supports transfer of equipment, trainings and expert advice on the establishment of protocols needed along the Pilot plant development action plans. It also envisages the assessment and validation process of the technology transferred through cost benefit analysis and feasibility models development for candidate/countries.

Output 2.4: Phase 2: Demo Plant with public/private partners operational, bringing this technology to commercial scale.

This output focuses on supporting the set-up process for a demo plant, as well as providing expert advice and supervision of the plant irradiation machine installed and operational.

3.3. Economic modelling

Marine litter is associated with costs of US $13 billion a year, mainly through its adverse effect on fisheries, tourism and biodiversity [32]. The overall social and environmental cost of plastic pollution is estimated at US $139 billion a year [33]. Of that, half arises from the climate effects of greenhouse-gas emissions that are linked to the production and transportation of plastic. Another third arises from the impact of associated air, water and land pollution on health, crops and the environment, plus the cost of waste disposal. Any effort to reduce this social burden would be a positive result to which the IAEA contributes.

Value-added of nuclear technologies on the overall plastic value chain

This section presents the methodological approach used to estimate the contribution that nuclear-based technologies could bring to accelerate the transition to a circular plastic economy. The approach will help to better estimate the 'value-added' that nuclear and nuclear-derived technologies can bring about into the plastics value chain. Spelling out the expected value addition from these experimental technologies helps to connect laboratories with commercial recycling plants, other private sector entities and technical validation initiatives supported by technical cooperation programmes, thus reducing the time-lag of technology transfers and increasing the effectiveness of the IAEA's efforts.

The methodological approach plays out at two levels, using advanced economic and financial modelling systems.

First, a preliminary cost-benefit analysis for different plant scales was undertaken to assess the potential advantage these plants could have in comparison to existing facilities. The analysis was based on the assumption that irradiation technology can improve existing recycling processes and generate higher quality pellets through an energy-saving process with overall lower input costs.[16] This methodological approach will be applied during implementation to ensure a sound validation of the technology, updating key market and industry related data once it becomes available and to contextualize each specific proposal as necessary.

Second, expected benefits from NUTEC Plastics coordinated actions have been enumerated, comparing the current situation with the potential impact of introducing these new technologies. This has been done by means of sensitivity analysis of the P2O model referenced above. Specific parameters of the P2O model were identified and modified to reflect technological improvements assumed in the micro level models. Additional work will be carried out to include expected benefits from the increased marine microplastic monitoring capabilities and related science-based decision making once detailed information becomes available.

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[16] Assumptions based on the conclusions of the 27-30 October 2020 virtual expert consultation meeting held by the IAEA, confirming that radiolysis can reduce pyrolysis temperatures by 150 degrees equal to energy savings up to 700Kj/Kg, reaffirming findings of Ponomarev, A. V. (2020). Radiolysis as a Powerful Tool for Polymer Waste Recycling. *High Energy Chemistry*, 54, 194-204.

Through the P2O model, the potential reduction that radiation technology may provide in terms of reduced leakage of plastics to the ocean was tested. The modelling exercise reveals that radiation technology, if deployed alongside the sorting process or the mechanical or chemical recycling process would reduce marine litter. As Figure 6 below shows, radiation alongside formal sorting reduces litter by 1.83kg/MT and alongside mechanical recycling by 2.3kg/MT. The highest reduction in marine litter would be achieved if radiation technology were deployed alongside the chemical conversion to monomers and to hydrocarbons (4.41kg/MT). The analysis concluded that through complementing chemical conversion with radiation, **the estimated reduction in ocean littering is more than two times higher** than the one obtained by deploying radiation technology in the sorting process or alongside mechanical recycling.

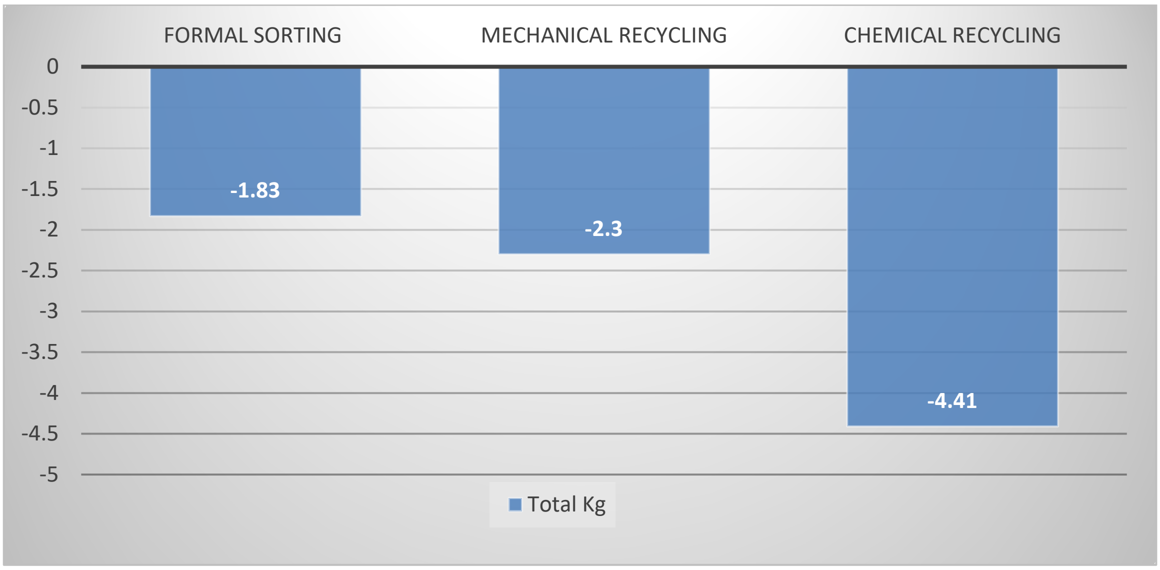

FIG. 6. Potential reduction in ocean leakage by deploying radiation technology alongside conventional technologies per MT. Own elaboration based on P2O model tools.

These are preliminary results based on assumptions related to the improved recycling technologies. These results are conservative, as recycled plastic accounts only for 9% of the overall plastic waste management equation, however, a dynamic model, taking into consideration expected increases in recycling volumes (to up to 60%) is under development to examine the effect that new technologies introduced by NUTEC Plastics may have as part of an overall transition to a circular economy [34].

3.4. Sustainability, risks and mitigation

Achieving an overall transition to a circular plastic economy relies on the greater efficiency and cost-effectiveness of reused and recycled plastic over new fossil-based plastic. The competitive advantage that radiation technologies deliver is a key element for the successful realization.

A comprehensive management results and monitoring tool will track progress in implementation and expenditures related to activities under NUTEC Plastics, and the P2O model referenced above will be used in the assessment and projection of results achieved. The model will also allow for identification of main bottlenecks in the expected flow of specific interventions, making it possible to address focused interventions to solve shortcomings in the sustainability of the transition towards a circular plastic economy. These arguments will pave the way to considering plastic not as waste but rather as a valuable raw material.

There are multiple uncertainties surrounding the different possible scenarios to achieve NUTEC Plastic's objectives and they depend on a range of factors and actors that are beyond the control of NUTEC Plastics. While developing the theory of change, a set of key pre-conditions was identified, and assumptions were made regarding related actions that need to take place for NUTEC Plastics to achieve its intended results. If any of these fails to materialize, they could constitute a risk for NUTEC Plastics.

3.5. Resource requirements and financing

Strengthening the capacity of a marine laboratory would cost approximately €1.1 million (including needs assessment, capacity building and equipment) and the cost of an irradiation pilot plant would be approximately €2.1 million (including capacity building, feasibility studies and equipment/construction). These are indicative figures. Specific NUTEC Plastics projects and budgets will be prepared in consultation with specific requesting Member States. The financial requirements of specific projects will accordingly be determined.

4. Partnerships

The global plastics problem is transboundary in nature and impacts all countries around the world, with developing economies experiencing the heaviest burden. Issues along the plastic value chain persist and a diverse set of actors are involved in resolving them. The IAEA's mandate covers only part of the plastics value chain through the application of nuclear science and technology as complementary to existing methods. A holistic and sustainable solution to the global plastic burden demands an integrated and comprehensive approach that can only be achieved in partnership with complementary players. Working with existing national, regional and international initiatives, at both global and country levels will be essential. This includes collaboration with United Nations entities, multilateral development banks, philanthropies, existing large-scale partnerships including multi-stakeholder platforms, the private sector as well as established private-public partnership initiatives, and scientific and research institutions.

The IAEA intends to provide added value to existing partnerships addressing the global plastic challenge. It will do this through:

- providing partners with an accurate assessment of the characterization of plastics, their abundance, distribution, and impact, in order to inform environmental policy making and management decisions.
- offering novel plastic recycling options through radiation technologies to complement conventional methods to fill existing gaps that so far have not yet been addressed by any plastic waste initiative.

To achieve this, the IAEA will step up its engagement with relevant partners to increase the awareness of the unique advantages of nuclear technologies to complement existing ones and to seek partnerships to accelerate the transition to a circular plastic economy.

The IAEA intends to strengthen its collaboration with sister organizations within the UN system who are working on complementary aspects of the global plastics challenge. These include, IOC-UNESCO, FAO, UNDP, UNEP, and UNIDO who are also involved in the Decade of Ocean Science for Sustainable Development, of which the IAEA is also an official partner. The IAEA is already partnering with many of these organisations who are working directly or indirectly on global plastic waste and its various impacts on land, the oceans and the atmosphere.

The private sector will be a critically important partner in making the transition to a circular plastic economy, underpinned by strong governmental action and ownership through enabling policies and supportive legal environment. The IAEA will therefore collaborate with existing high-profile public-private partnerships (e.g. GPAP), foundations, private sector associations, as well private sector companies producing plastic products to test and apply the feasibility and effectiveness of radiation for plastics recycling. Leveraging partnerships with the business community, well-established public-private partnerships, foundations, plastic associations and other relevant stakeholders will raise awareness of the benefits of nuclear science and technology in addressing plastic waste where technological innovations and innovative solutions are applied in practice and broker outreach to networks of other potential partners.

Cognizant of the large-scale investments necessary for the necessary transition to more sustainable plastic management practices, the IAEA will work closely with international financial institutions and development finance institutions as backbone investors in national and private sector efforts for closing the loop of the circular plastic economy.

Cooperation with other technical and scientific institutions will be sought for exchange of information and for leveraging contributions, such as:

- Research institutions that focus on plastic pollution in Arctic snow/ice cores such as the German Alfred Wegener Institute Helmholtz Centre for Polar and Marine Research; the Swiss Institute for Snow and Avalanche Research; the Research Council of Norway; the Danish Centre for Marine Research; the British Antarctic Survey; the Norwegian Polar Institute; ArcticNet, and others.
- Stakeholders with complex system modelling capabilities, such as the World Meteorological Organization (WMO), the US Geological Survey (USGS) and the International Centre for Theoretical Physics.

5. Implementation

5.1. Implementation approach

The activities described in this NUTEC Plastics document will be implemented using a variety of established IAEA implementation mechanisms such as TC projects, CRPs and other programmatic activities. NUTEC Plastics' two main components — marine monitoring and recycling/reuse — are logically intertwined as both represent a contribution to the solution of the global plastic pollution problem. However, they are operationally independent, as the implementation of activities in one component is not contingent on the implementation of the other. NUTEC Plastics takes this connected but not co-dependent relationship of the two components into consideration by adopting a **modular approach to implementation**. The advantage of this approach is twofold:

First, a modular approach is best suited to accommodate different needs, preferences and capacities of countries to address their specific plastics problem. In some cases, this may entail the need for more accurate monitoring and assessment of marine plastic pollution, in other cases it may be upgrading of plastic recycling facilities with radiation technology, in yet other circumstances, countries may want to opt for both components. A modular approach ensures that the implementation is carried out with the utmost degree of flexibility, firmly based on the needs and priorities of Member States.

Second, a modular approach offers flexibility in mobilizing and securing the necessary financial (and non-financial) resources, thus enabling early implementation to begin. Implementation of specific NUTEC Plastics activities can begin as soon as 'seed' resources become available, while remaining resources are being secured. This approach has the additional advantage of allowing donors and partners to engage in specific activities, depending on their preferences and priorities.

There are over 40 ongoing or planned TC projects, CRPs and other programmatic activities that relate to radiation technologies and environmental monitoring. Of these, more than 25 projects are directly related to plastics. These projects could expand their scope to include NUTEC Plastic activities as necessary.

Countries that would like to engage with NUTEC Plastics activities, either with the recycling or with the monitoring component (or both), will be asked to consider the following criteria:

- Extent of the national/regional plastic waste problem.

- Strong political commitment to address plastic waste pollution, evidenced by respective policies, plans, targets, in addition to strong and strategic links among their respective national institutions, relevant regional networks and cooperation platforms.
- Plastics waste collection and separation through formal or informal plastic waste management.
- Ongoing participation in plastic waste initiatives. This will ensure that the whole plastic value chain is addressed and will ensure that the IAEA contribution and impact will be greater than with a standalone intervention.
- Commitment to increasing the understanding of the marine effects of microplastic pollution.
- Existing capacity in irradiation technologies and/or marine environmental analyses.
- Experience in working with the IAEA in the field of nuclear techniques and applications, such as through IAEA Collaborating Centres.
- The necessary regulatory environment is in place for the use of radiation techniques or willingness to put these in place.
- A relevant private (plastic) sector that is engaged, experienced and/or open to collaborating through public-private partnerships (PPP).

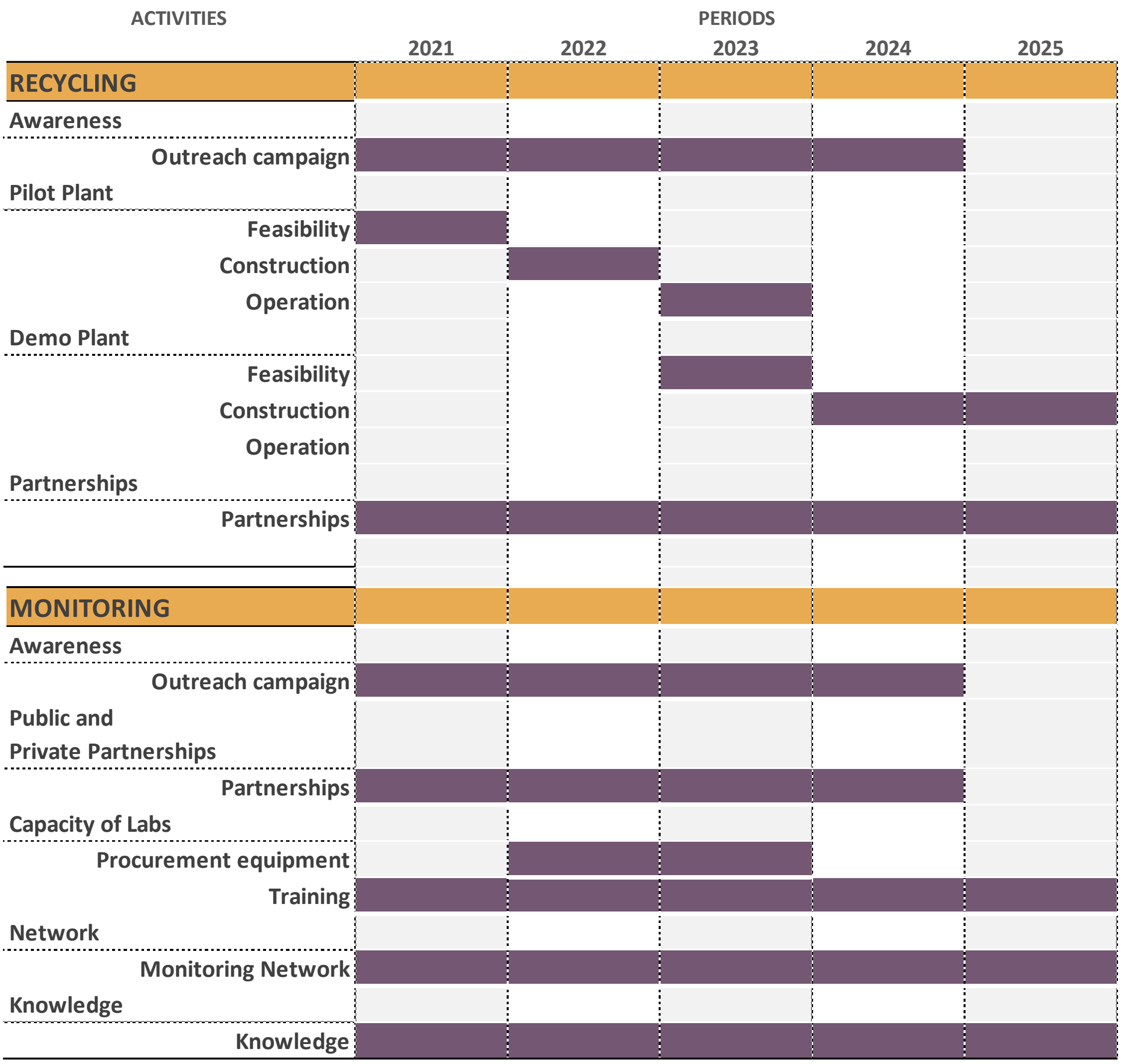

FIG. 7. NUTEC Plastic implementation schedule.

5.2. Monitoring and evaluation

Each of the implementation modalities (TC projects, CRPs, other programmatic activities) will use their respective standard monitoring, evaluation and reporting procedures and mechanisms. At the core of the IAEA's M&E system lies the results-based approach making use of the logframe, indicators, means of verification and assumptions. NUTEC Plastics includes indicators of results for each component. A detailed monitoring and management tool has been developed. The indicators will be monitored during implementation and progress will be documented in biannual reports. Given that NUTEC Plastics is acting in a changing environment where other stakeholders play major roles, some of the assumptions adopted in the theory of change are key factors in the successful achievement of results. These assumptions will be closely monitored during implementation as part of the risk management framework and corrective actions taken in case they do not materialize and become a risk for the achievement of any of the components of NUTEC Plastics.

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