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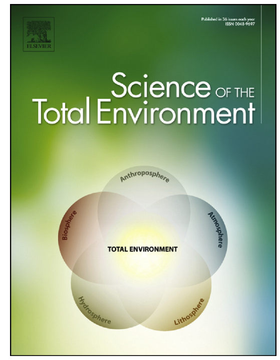

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Material Flow Analysis of Plastic Waste in the Gulf Co-operation Countries (GCC) and the Arabian Gulf: focusing on Qatar

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Abstract

Global plastic waste production has increased dramatically in recent years, both globally and regionally, having a multitude of adverse effects on the environment and human health. However, little attention has been directed to this problem in the Arabian Gulf region. This study aims to delineate and map the status of the plastic waste problem in the Gulf Co-operation Countries (GCC), with a focus on Qatar. The study, focuses on the plastic waste in the marine environment, depicting the different types, sizes and shapes of plastic particles found in the Arabian Gulf. To depict the flow of plastic waste, a generic material flow diagram was built using a material flow analysis software named STAN, in which transfer coefficients were assigned based on existing scientific literature and estimations built on data from local industries and recycling facilities. The recovery and recycling efforts that have been made by the different GCC countries, in efforts to reduce plastic waste and minimize the risk of plastic on the environment are analyzed, too. Our analyses indicate that approximately 11.9 Mt ±595.395 Kt of plastic waste is produced annually in the GCC region, of which only 23±15% is recycled, indicating that improvements are yet to be made in the recovery, recycling and treatment of plastics in the region. However, in Qatar, a higher percentage of plastics (40±10%) is recovered-recycled with efforts to treat plastics and reuse it to generate energy.

Keywords: Plastic waste; marine litter; Arabian Gulf; Qatar; recycling; material flow analysis

ABBREVIATIONS

C&D	Construction and Demolition
DSWM	Domestic Solid Waste Management
GCC	Gulf Cooperation Council
HDPE	High density polyethylene
kt	Kilotonnes
LDPE	Low-density polyethylene
LLDPE	Linear low-density polyethylene
MFA	Material Flow Analysis
MFD	Material Flow Diagram
MPs	Microplastics
MSW	Municipal Solid Waste
Mt	Million Tonnes
PE	Polyethylene
PET	Polyethylene terephthalate
PP	Polypropylene
PS	Polystyrene
PVC	Polyvinyl chloride
QEERI	Qatar Environment and Energy Research Institute
QNV2030	Qatar National Vision 2030
UAE	United Arab of Emirates

1. Introduction

Plastic was first developed in the early 1900's, and since then, the use and dependency on synthetic polymers has increased unwaveringly (Shen and Worrell 2014). Plastic has a wide range of applications and is used in almost every sector, including industrial machinery, building and construction, textiles, medicinal uses, transportation and electronics (Wright et al. 2013). This is due to its high flexibility, versatility and durability which makes the use of plastics convenient and inexpensive (Martín-Lara et al. 2021, Thompson et al. 2009). However, as the dependency on plastics has increased, the generation of plastic waste around the world, has also intensified greatly. According to PlasticsEurope and EPRO (the European Association of Plastics Recycling and Recovery Organisations), the global production of plastics in 2019 has reached almost 370 Mt, 7% of which is produced in the Middle East and Africa (PlasticsEurope 2020).

As a result, there has been growing concern over the increase in plastic production, specifically within the marine environment as plastics have been accumulating within the world's oceans for the past 40 years (Aydın et al. 2016, Wright et al. 2013). According to the United Nations Environment programme (UNEP), marine litter is defined as "any persistent, manufactured or processed solid material discarded, disposed of or abandoned in the marine and coastal environment" (UNEP/MAP 2011). Of all the marine litter present in the oceans worldwide, plastic is the most prevalent accounting for 60%-80% of the total marine debris, depending on sources (Derraik 2002). Plastic marine litter can originate from different sources and has a wide range of adverse effects on the marine environment and human health and safety (Hahladakis 2020a, b). For instance, plastics can enter the marine environment when inadequately managed and mishandled (Derraik 2002), or as a result of public littering by the beach (Moore 2008). Plastic marine litter can also originate from marine based activities such as boating, shipping and fishing (Özden et al. 2021) which are responsible for approximately 20-30% of the plastic waste that is discarded into the oceans; commercial fishing is the most prevalent type of activity and accounts for most of the marine plastic waste in the world (Gennip et al. 2019). Plastics can also end up in the marine environment by rivers and as a result of municipal drainage systems, industrial discharges and run-offs (Veerasingam et al. 2020). Other sources have traced back the presence of microplastics (MPs) to two sources, primary and secondary (Al-Salem et al. 2020). Primary sources of MPs are initially produced to be of microscopic size, and mainly derive from facial cosmetics, abrasive blasting or virgin plastic pellets, while secondary sources describe MPs that arise due to the breakdown of larger plastic debris by wave action and abrasion (Cole et al. 2011). Additionally, the leaching of various additives present in plastic, into the marine environment, contribute to marine pollution, (Hahladakis et al. 2018), as does the natural breakdown of larger plastic particles into smaller fragments (Koelmans et al. 2014).

It was estimated that in 2010, approximately 4.8 to 12.7 Mt of plastic litter from land-based sources was introduced into oceans, and this number is only expected to increase in the next ten years (Jambeck et al. 2015). The deleterious effects of plastics when present in the marine environment are abundant and can completely alter the surrounding ecology (Galloway et al. 2017), causing changes in the biodiversity, thus leading to uncertain secondary consequences (Beaumont et al. 2019). Plastic is a manmade item and therefore, acts as a stressor when introduced in the marine environment. Further than that, the impact on marine life can be disastrous when the effect of plastic is coupled with other environmental stressors such as varying ocean temperatures, ocean acidification and the presence of other pollutants (Beaumont et al. 2019).

However, perhaps one of the discernible effects of plastic pollution on marine organisms is the life endangerment it causes due to entanglement and smothering in marine debris, which consequently interferes with their mobility, breathing and feeding patterns (Kühn et al. 2015). Additionally, due to the small size of MPs, which is <5 mm (Andrady 2011), they can be easily ingested by different types of zooplankton, negatively affecting biological processes in the ecosystem. Zooplankton is a vital food source for multiple secondary consumers and therefore, MPs travel up the trophic levels and accumulate in the process (Botterell et al. 2019). Recycling is a well-known method of disposal for reducing the amount of net discard of plastic solid waste in the waste stream and lowering the overall adverse effects of plastics in the environment (Shent et al. 1999). However, one of the most common problems with plastic recycling is the complexity that comes with it due to the different types of plastics, additives and composites (Shen and Worrell 2014). Therefore, different countries adopt different recycling strategies depending on the economic benefit. Recycling methods can range from incineration with energy recovery, downcycling processes and circular economy processes.

The aforementioned reasons should be enough to encourage immediate change, however, in the Arabian Gulf region much work needs to be done to manage and control plastic. In this study, we mainly aimed at delineating and mapping the plastic waste generated in a) the Arabian Gulf, b) the GCC countries, and c) Qatar, while taking into account the classification of plastics entering the marine environment according to their sizes (-macro, -micro, -nano), types and shapes. This was done by using an existing material flow analysis software to create a material flow diagram (MFD) (Damghani et al. 2008). The MFA required a review of the different recovery and recycling initiatives taken by the countries in the region, and we summarize this review at part of the paper.

2. Materials and Methods

2.1 Literature Review

Data concerning the plastic waste production in the region, as well as the fate of plastics and the recycling efforts, were extracted through an extensive review of literature on marine litter and plastics in the Arabian Gulf area and Qatar. The primary tool used for this review was expanded scientific based investigation using the respective databases (‘ScienceDirect®’, ‘Google Scholar®’, ‘Scopus®’ and ‘Researchgate®’). After searching using keywords e.g. Marine litter, Plastics, Arabian Gulf and Qatar in all possible combinations the articles were limited to those focusing on plastic marine litter in the Arabian Gulf. It should be noted that due to insufficient number of sources and quantitative data about the recycling efforts in the region, certain assumptions had to be made based on the available information in published articles. The crucial aspects reviewed were the quantitative data on the plastic waste reaching the marine environment, with a focus on the type of plastic, their size, shape and possible sources. Other aspects included the potential routes and final destination of the plastic waste, whether it was landfills and open dumpsites, recovery and/or recycling. Finally, part of the literature review included gathering information based on local entities that deal with plastic waste (namely ministries and their websites and local recycling facilities).

2.2 Data from Unpublished Sources and Grey Literature (used for the Qatar based MFD)

In order to collect information regarding recycling in Qatar, several phone calls and meetings were had with various recycling businesses, such as Asima Plastic Factory and Doha Plastic Company. Furthermore, via different contacts with experts and engineers, assumptions and transfer coefficients were determined about recycling attempts in the country. Several other local resources included the State of Qatar's Ministry of Commerce and Industry website where comprehensive reports were found about every plastic recycling activity taken place by registered companies in the country. Information included the full company profile along with data about capacity and production of recycled plastics in tons per year (from 2017 to 2021); for the sake of this study, we only considered the company profiles for the year 2017, so as to be consistent with the information/year used in the MFD. Local news articles were also taken into account. Finally, we also conducted meetings with senior research directors and scientists at the Qatar Environment and Energy Research Institute (QEERI), in order to gain any additional information on new recycling initiatives taken locally.

2.3 STAN Software

The main focus of this study was to construct a material flow analysis diagram using the STAN (2.6.801) software (sub**ST**ance flow **AN**alysis). As defined by the creators of the software, STAN is a convenient freeware which helps perform material flow analysis with regards to specific data uncertainties (Cencic and Rechberger 2008). The software is based on the law of mass conservation, where the mass that enters a system in a MFD, must accumulate in the system or leave the system fully (Bureecam et al. 2017). This makes STAN software beneficial when it comes to unknown or inconsistent data as it uses its algorithm to automatically calculate such values when sufficient information is provided at the start. Two MFDs were constructed for this study, one for the entire Arabian Gulf area which include the countries: Iran, Iraq, Kuwait, KSA, Qatar, Bahrain, UAE and Oman, and the other one specifically for Qatar. Both values inserted as an initial point at the MFD were the generation of waste -in tons- for 2016, for the Arabian Gulf Countries and 2017, for Qatar. The rest of the MFD was developed based on transfer coefficients and percentages-assumptions mostly extracted from scientific literature, for the respective years, as well as grey literature and calculations of the authors. Building an MFD consists of the following: 1) developing a graphical model with defined processes, systems and flows, 2) creating subsystems within certain processes of the MFD, thus providing a more detailed view on the respective process, 3) balancing the MFD as per the mass conservation law, 4) inserting transfer coefficients, 5) and calculating the substance flows.

In this study, an in-depth research of the nature of the plastic waste in the region was done based on existing literature and, a generic MFD was created to depict the flow of plastic waste using STAN software, extending from the generation of plastic waste, to collection, recovery, recycling and finally exportation.

The main processes/systems in our MFD included the: generation of municipal solid waste (MSW), generation of plastic waste, litter, marine litter, collection of plastic waste, plastic waste sent to landfills, to open dumpsites, for recovery, for recycling and being exports. Subsystems were, created to give more detailed information on various processes. The main subsystems included the marine litter process, where quantitative data about the type, shape and size of plastics found in the marine environment is shown. A subsystem was also created for the recycling process to show the different recycling "routes" followed in the region.

3. Results and Discussion

3.1. GCC Region

3.1.1 Material Flow Analysis of Plastic waste in the GCC Region.

Fig.1. shows the MFD for the Arabian Gulf region started with the generation of MSW which amounts to 11.9 Mt/year (for the year 2016), as evidenced by (Ghayebzadeh et al. 2020).

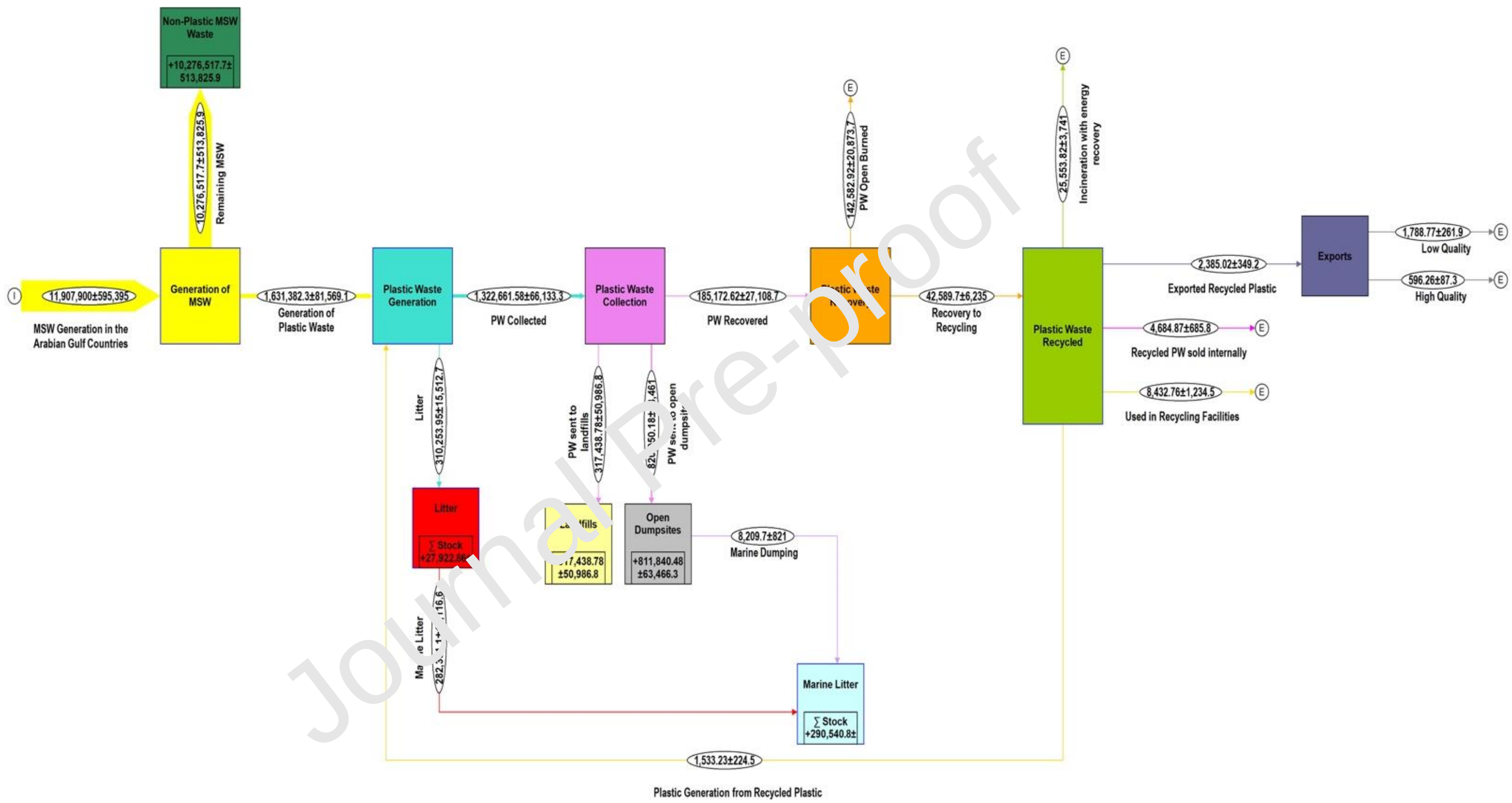

Figure 1. MFD of plastic waste in the GCC region for the year 2016.

MSW is categorized into six different groups and can consist of anything from food residue, wood, glass, textiles, paper and plastics (Noor et al. 2020). The MSW generation flow is split into different flows which are proportionate to the amount of MSW that is generated by each country in the region. In general, regarding the highest percentages of MSW generation in the region, the United Arab of Emirates (UAE) was the highest MSW generator with 37% of the total MSW in the Arabian Gulf region, equaling 4.4 Mt. Kuwait had the second highest percentage with 19.26%, followed by Saudi Arabia with 18.4%, Qatar with 10% and finally Bahrain with 8%. The high amount of MSW produced can be attributed to the sudden economic growth that the GCC countries have faced in the past few decades, following the discovery of oil. Due to the global energy demand that succeeded after the widespread of industrialization and globalization, the need for oil had dramatically increased which drove the oil prices up around the world (Osman et al. 2016). The amount of waste generated can be attributed to the increase in human population which itself stems from the economic growth and job opportunities in the region. In turn, this has led to a high population growth in the region in a short amount of time, resulting in high gross domestic product and hence, the increase in waste generation rate (Ebrahimi et al. 2016). Another reason for the high generation of MSW in the GCC countries is associated with the great extent of food waste at the consumer level (El Bilali and Ben Hassen 2020). In contrast, Oman was the lowest producer of MSW in the region with only a percentage of lower than 0.4%, followed by Iraq with a percentage 0.4% and Iran being the third lowest generator of MSW with a percentage of 6.4%. The difference of numbers regarding the generation of MSW in each country is dependent on different factors, such as the geographic location, socioeconomic factors, common habits and lifestyle of the population, as well as the public awareness (Al-Jarallah and Aleisa 2014, Damghani et al. 2008, Ghayebzadeh et al. 2020). Additionally, the financial state of a country is strongly associated with the waste generation rate; for instance, low-income countries with a GDP under $5000 (USD) per capita, generally, have lower MSW generation rates, ranging from 0.3 to 0.9 kg/capita/day, whereas countries with higher GDPs per capita, MSW generation may reach up to 1.4 to 2.0 kg/capita/day (Al-Jarallah and Aleisa 2014).

However, in this study we solely focus on the generation and flow of plastics which in 2016, was approximated to be 13.7% of the total MSW flow, equalling 1.6 Mt ± 82 Kt of plastic waste per year, as has been evidenced by (Ghayebzadeh et al. 2020). The percentage of plastic waste produced from the total MSW in this study (13.7%), is consistent with the findings of (Hahladakis and Aljabri 2019), who have estimated that plastic waste accounts for aproximately 13-14% of the total MSW. In the plastic waste stream, the UAE had the highest share of plastic waste generation with about 51.4% of the total plastic waste in the Arabian Gulf region, which is compatible with the amount of MSW that is generated. Kuwait, is the second highest producer of plastic waste with 18.2% of out of the total plastic waste generation, followed by Qatar with 10.2%. The high percentages of plastic waste production are associated with the economic growth in the region, causing rapid urbanization activities and high buying power, accompanied with the lack of awareness for sustainable practices when managing waste (AlMa'adeed et al. 2012). The trend of plastic waste generation has been rising in the past few years and is only expected to increase, as is expressed in many studies conducted in the region (Al-Salem et al. 2020, Ghayebzadeh et al. 2020, Hadidi and Omer 2017). The most common types of plastic produced in the Arabian Gulf region, specifically within the GCC countries are polypropylene (Sussarellu et al.), high density polyethylene (HDPE), linear low-density polyethylene (LLDPE) and low-density polyethylene (LDPE); based on the findings of (Al-Salem et al. 2020), the following assumptions were made about the generation of each type of plastic for the Arabian Gulf region; 44%, 30%, 17% and 9%, respectively. This can be explained by the common phenomenon where countries in the Arabian region are moving towards the mass production of plastics. For instance, ethylene production is intensifying in the Asian market through various industries in Saudi Arabia, Kuwait and the UAE (Al-Salem et al. 2020). Kuwait alone, produces around a million tons of different polymer grades and plastic items every year, ranging from packaging materials, PET bottles and plastic bags which make up most of the domestic plastic waste in Kuwait (Al-Salem 2009). Additionally, Iran's use of different types of polymers such as polyethylene (Hodgson et al.), polyvinyl chloride (PVC) and other types of resin has multiplied by 20 times from the years 1978 to 2014, and its petrochemical capacity has reached approx. 60 million tonnes per year (Al-Salem et al. 2020)

After the generation of plastic waste, the flow is split into two: plastic collection and litter. Litter includes both land and marine litter, and it is estimated to be 19±5% of the total plastic waste that ends up being discarded (Ghayebzadeh et al. 2020). Within the litter subsystem, the process is split into two, with land litter accounting for 9±5% of the total littered plastic waste, and marine litter having the highest share with 91±10%, equaling 280 kt, as per the study of (Ghayebzadeh et al. 2020) for the year 2016. The amount of plastic waste that is not littered, is considered to be collected. Based on the STAN software principle where the mass of the products in a reaction must be equal to the mass of the reactants, the amount of plastic collected was calculated by the software, to be 81% of the total plastic waste generated.

Further than that, the plastic waste collected is divided into three separate flows that go into their own processes: landfills, open dumpsites and plastic waste recovery. (Ghayebzadeh et al. 2020) divided the waste management process into two categories, adequately managed practices such as sanitary or controlled landfills, recycling or incineration, whilst the second category is inadequately managed practices that include open dumpsites and non-sanitary landfills. As it can be seen from Fig. 1, the majority of plastic waste collected in the Arabian Gulf region ends up being inadequately managed and in open dumpsites (62±8%), triggering a broad range of detrimental effects on the environment and human health. There are many explanations for this high number, mostly relating to the nature of the waste management practices conducted in the country. For instance, in Kuwait there seems to be a lack of legislation which would impose laws for recycling, as well as an absence of public awareness concerning sustainable plastic waste management, both on an individual, consumer level, and on a national level (Al-Jarallah and Aleisa 2014, Al-Yaqout and Hamoda 2002). For Iraq the inadequate management of waste can be ascribed to the insufficient funds to properly set up an efficient, sustainable waste management site with environmental control schemes, lack of appropriate control, monitoring and regulation, as well as the absence of legitimate recycling facilities (Abdulredha et al. 2020). In Oman, there is a lack of appropriate collection and disposal facilities, directing little importance to management of waste and insufficient availability of recycling infrastructure (Ghayebzadeh et al. 2020), whilst in Bahrain inadequate waste management is attributed to rapid population growth coupled with fast growing industrial activities, along with poor waste management legislation. The UAE also had experienced high rates of population growth in the past few decades, which comes along with rapid urbanization; combined with the inadequate waste management practices resulting in poor disposal of waste (Almansoori and Moussa 2017, Ghayebzadeh et al. 2020). In a study that reviewed the solid waste management practices in Saudi Arabia, it was found that the prevailing method of waste management is simply collecting the waste and dumping it in non-engineered landfills where there is a high risk of leaching and release of gases (Miandad et al. 2016). There seems to be a trend of inadequate waste management in most of the countries in the Arabian Gulf region, slightly varying depending on the population number, waste generation rates and rate of development. However, it is agreed in multiple studies that appropriate waste management practices must be adopted, and strict legislation must be put into place, along with regular monitoring, in order to ensure the safe and secure treatment of waste.

Controlled landfills are the next common disposal method of collected plastic waste in the Arabian Gulf region. A percentage of 24±16% was assigned for this flow, amounting to 318 kt ±51 kt per annum. Landfilling is the most prevalent, and perhaps only, way of controlled and appropriate management of waste in the Arabian Gulf, considering that the landfilling costs are very low, compared to the recycling cost rates in the region (Loukil and Rouached 2012). For instance, all the efforts in waste management in Iraq have been restricted in collecting waste and landfilling it (Musheb 2018). In Saudi Arabia, a large portion of construction and demolition (C&D) waste is sent to landfills (86.4%), which leads to the assumption that landfilling is also the most common controlled way of managing plastic waste (Ouda et al. 2018). As per the Arab Forum for Environment and Development (AFED) report in 2020, Kuwait's MSW is only disposed of in landfills, while in Oman there are 350 dumpsites and landfills, making it the predominant type of waste management; Qatar is also mainly dependent on landfills, as well as the UAE (Saab and Habib 2020). Next is the plastic waste recovery processes where it is estimated that 14% of the collected waste is actually recovered, 23±15% of which is recycled and 77±15% is openly burned.

3.1.2 Material Flow Analysis of Marine Plastic Waste in the Arabian Gulf

The predicted mass of plastic waste inflow to the marine environment is demonstrated by Fig. 2 where it is estimated that approx. 280 kt ± 14 kt of plastic waste is introduced into the Arabian Gulf waters every year. This assumption was based on the study by (Ghayebzadeh et al. 2020), who predicted that around 155 to 413 kt of plastic waste enters the Arabian Gulf, and so an average was taken for the sake of this study. A second flow that enters the marine litter process in Fig. 2 is the potential marine dumping from open dumpsites (1±10%). Open dumpsites are a source of marine pollution due to the leachate mismanagement and regulation of flows (Ferronato and Torretta 2019).

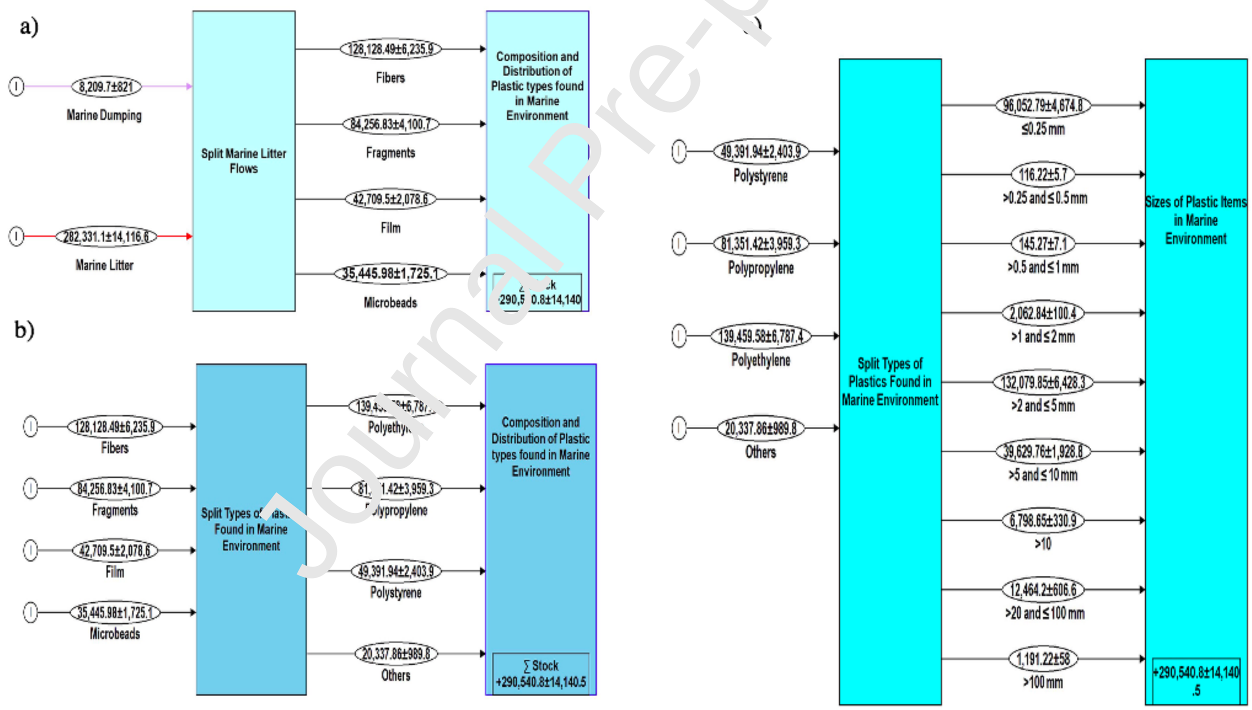

Figure 2. MFD of the marine litter subsystem in the entire Arabian Gulf (GCC) region with regards to: (a) particle types, (b) polymer types (c) plastic sizes

The high abundance of plastic litter in the marine environment can be due to the high fishing activities that commonly happens in coastal areas, and the unsuitable plastic disposal by fishermen, which refers to the the massive volumes of commercial fishing gear, such as nets, lines, and traps, that are discarded in the oceans and seas every year, accounting for the vast bulk of big plastic pollution in the marine environment (Dobaradaran et al. 2018). Other areas in the Arabian Gulf, especially those that are frequently visited by tourists contribute a high number of plastics into the marine environment through direct littering by beachgoers and recreational activities (Naji et al. 2017). Coupled with the lack of cleanup programs and a proper solid waste management system, MPs can become readily available to marine organisms. Sewage effluent outlets situated on the coasts of countries, also greatly contribute to the introduction of plastics in the marine environment, as is the case for the Richahr beach in Iran (Dobaradaran et al. 2018).

As is shown in Fig. 2a fibers were the most commonly identified shape of MPs in the Arabian Gulf with an average of 44±5%, followed by fragments (29±5%), film (15±5%), and microbeads (12±5%) (Kor and Mehdinia 2020). In other analyses of MPs in the Arabian Gulf, fibers were also the most abundant microplastic type in seawater (Castillo et al. 2016), across beach sites (Naji et al. 2017), and in different tissues of fish and prawn (Abbasi et al. 2018). These findings were consistent with that of (Woods et al. 2018), who stated that microplastic fibers are the most pervasive marine contaminant, comprising 90% of global microplastic concentrations. A possible explanation for this is that fibers are known mostly as nylon and polyethylene terephthalate (PET), both of which are types of polymers, usually found in clothing (Naji et al. 2017). Fibers make up most of the clothing and textiles because of their low cost and versatility, leading them to be used extensively (Hocking 2005). As a result, the main source of fibers being introduced into the marine environment, is from the disposal of municipal wastewater from washing clothes (Kor and Mehdinia 2020, Naji et al. 2017). Therefore, it can be concluded that as the human population increases, so does the demand for more clothes and textiles, leading to increased fiber microplastic contamination in the marine environment. Nylon is also commonly used in fishing lines (Battisti et al. 2019), and in areas where intensified fishing activities occur, the fishing gear and discarded nets could be an important source of MPs (Naji et al. 2017). This is an expected result, since it has been reported that 18% of the marine plastic debris is a result of the fishing industry (Andrady 2011). Microbeads were found in the lowest quantity (12%), and this could be due to their small size or insufficient sample testing. Microbeads are considered to be primary MPs that are found in products used daily, such as facial cosmetics and soap products (Kor and Mehdinia 2020).

Fig. 2b displays the plastic types found in the Arabian Gulf, from where it can be seen that PE was the most ubiquitous with 48±5%, followed by PP (28±5%), polystyrene (PS) (17±5%) and other polymer types (7±5%) (Kor and Mehdinia 2020). These results corroborate the findings of another study that analyzed MPs in the Arabian Gulf, where it was reported that PET and PE were the most abundant (Naji et al. 2017). Comparison of the findings with those of other studies conducted in different parts of the world, confirm that PE and PP dominated sea surface samples (42% and 25%, respectively) (Erni-Cassola et al. 2019). This is not surprising considering that these materials are commonly used in single-use plastic packaging, which account for 74% of the total global plastic production in 2015 (Geyer et al. 2017). Classes of plastics such as PE, PP, PS and PET are widely used in plastic packaging and different materials such as plastic bags and bottles (Andrady 2011, Groh et al. 2019), and their high demand and utilization makes it more likely that they end up in the marine environment. PP, PE and PS fibers are also commonly used in textiles (Carney Almroth et al. 2018, Kor and Mehdinia 2020), and intensive industrial activities along the coasts of the Arabian Gulf can, also, be a likely source of PE, PP and PS that end up in the marine environment of the Gulf. It has also been theorized that the low specific densities of PE and PP, and the buoyant nature of PS, cause them to be widely spread across aqueous systems (Kor and Mehdinia 2020).

The distribution of plastics in the marine environment of the Arabian Gulf, according to size is demonstrated by Fig. 2c. Categories of plastic sizes (>2 and ≤ 5 mm), (≤0.25 mm) and (>5 and ≤ 10 mm) had the highest abundance of plastics with 45±5%, 33±5% and 14±5%, respectively (Dobaradaran et al. 2018). These results reflect those of (Kor and Mehdinia 2020), who also found that the smallest category size of MPs (1-3mm), detected in the Arabian Gulf is the most dominant, accounting for 32±5% of the total MPs. The prevalence of smaller size MPs in the marine environment can be attributed to the high residence time in the sea which can further deteriorate the plastic and break it down into smaller fragments (Dobaradaran et al. 2018). It is also worth noting that the Arabian Gulf is characterized by its arid and hot climate, both of which are environmental factors that exacerbate the degradation of plastic items due to the ample heat, light and UV exposure (Dobaradaran et al. 2018, Karkanorachaki et al. 2018). The abundance microplastic contaminants in the marine environment has deleterious effects on the ecosystems. This is because of the relationship between the particle size and surface area; as the particle size decreases, the surface area of said particle decreases.

Plastics have hydrophobic properties, and with increased surface area, more organic pollutants adsorb to the particles, thereby increasing the contamination of the marine environment (Kor and Mehdinia 2020). Furthermore, the pervasiveness of a smaller sized particle increases the possibility of it being ingested by marine organisms (Akhbarizadeh et al. 2018, Lusher et al. 2017); causing intestinal damage (Lei et al. 2018) and oxidative stress due to cellular impairment (Guzzetti et al. 2018). Smaller sized MPs become easily bioavailable to many species of planktons, thereby causing their bioaccumulation and trophic transfer to organisms higher up the food chain (Au et al. 2017). Consequently, their trophic accumulation becomes a concern for human health and food safety (Van Cauwenberghe and Janssen 2014).

3.1.3 Material Flow Analysis of Recycling Systems in the GCC Region

Literature about recycling activities in the region is scant, however on account for this study, the recycling percentage assigned for the GCC region was 23±15%, while the rest of the recovered plastics (77%) are either landfilled, openly disposed and/or, in turn, burned. It is apparent in literature that recycling activities in the region are not common and recycling programs in the GCC member states still remain unappealing, mainly due to the availability of land and low cost of landfills; all of which encourage these states to continue landfilling plastic wastes instead of recycling them (Alhumoud et al. 2004). For instance, in Iraq there is insufficient recycling activities due to lack of appropriate plans (Shuokr Qarani et al. 2011); the UAE has not reached its recycling goals as a result of lack of appropriate infrastructure for waste management, the recovery of materials and proper disposal of plastic waste (Janajreh et al. 2015); in Iran most of MSW does not undergo any recycling processes (Dehghanifard and Dehghani 2018); in Oman and Kuwait the majority of MSW ends up in landfills or incinerators (Omar et al. 2004, Saab and Habib 2020), in Qatar 13% of the plastic waste is collected (Hahladakis and Aljabri 2019) and 40% of the recovered waste undergoes recycling activities. As for Saudi Arabia, recycling and energy recovery methods are still at an early development stage, however, recycling rates range from 10-15% (Hakami and Abu Seif 2015); finally, Bahrain's material recovery is underdeveloped and recycling activities are restricted to preprocessing (Al Sabbagh et al. 2012). For the above reasons, a low percentage was assigned for the recycling activities that occur in the region. However, there is confidence that public awareness is increasing, and more sustainable waste management plans are being put into place within many countries in the GCC region.

Fig. 3 shows the different types of recycling processes that may occur in the region, mainly divided into downcycling processes and closed-loop recycling processes. For the reason that insufficient studies were available about plastic waste recycling in the region, several assumptions were made based on local information from Qatar. From the actual numbers that were found based on recycling information in Qatar, similar percentages and transfer coefficients were determined and applied for the entire region of the Arabian Gulf countries.

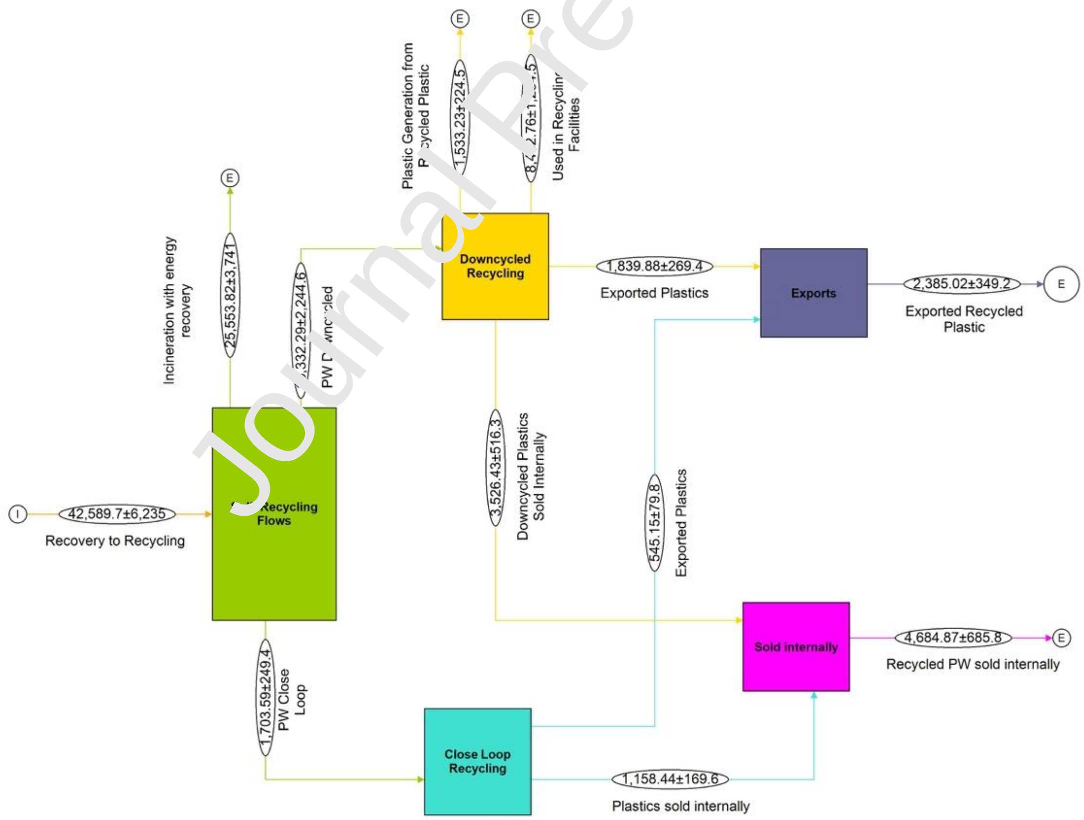

Figure 3. MFD of the recycling subsystem in the GCC region.

A percentage of 60±15% was assigned for the incineration of plastics with energy recovery, as a waste-to-energy form of recycling. From an economic perspective, the cost of conserving energy via recycling is much higher compared to waste incineration (Wollny et al. 2001), and the financial viability of the incineration method in the UAE was proven to be more feasible than any other methods, with more profit generated (Abdallah et al. 2018). Therefore, it is safe to assume that with the insufficient funding that some countries face in the region to set up proper waste management strategies (Abdulredha et al. 2020), and the economic feasibility of the strategy, the highest possible percentage should be assigned to the incineration with energy recovery method. A percentage of 36±15% was assigned to the downcycling processes in the region, while only 4±15% was allocated to the closed loop processes. Downcycling is the form of plastic recycling that involves transforming plastic items into products that are structurally and morphologically different than the original (La Mantia 2004). It is the most common form of recycling, in contrast to the closed loop recycling method which is largely dependent on the high quality of the plastic, making it rather difficult to attain (Hahladakis and Iacovidou 2018). The end products of downcycling and closed loop recycling are either used again in recycling facilities, sold internally or exported.

3.2 Qatar region

3.2.1 Material Flow Analysis of Plastic waste in Qatar

The MFD of plastic waste in Qatar is displayed in Fig. 4, starting with the generation of MSW that amounts to approx. 1 Mt ±50 kt, for the year 2017 (Al-Salem et al. 2020).

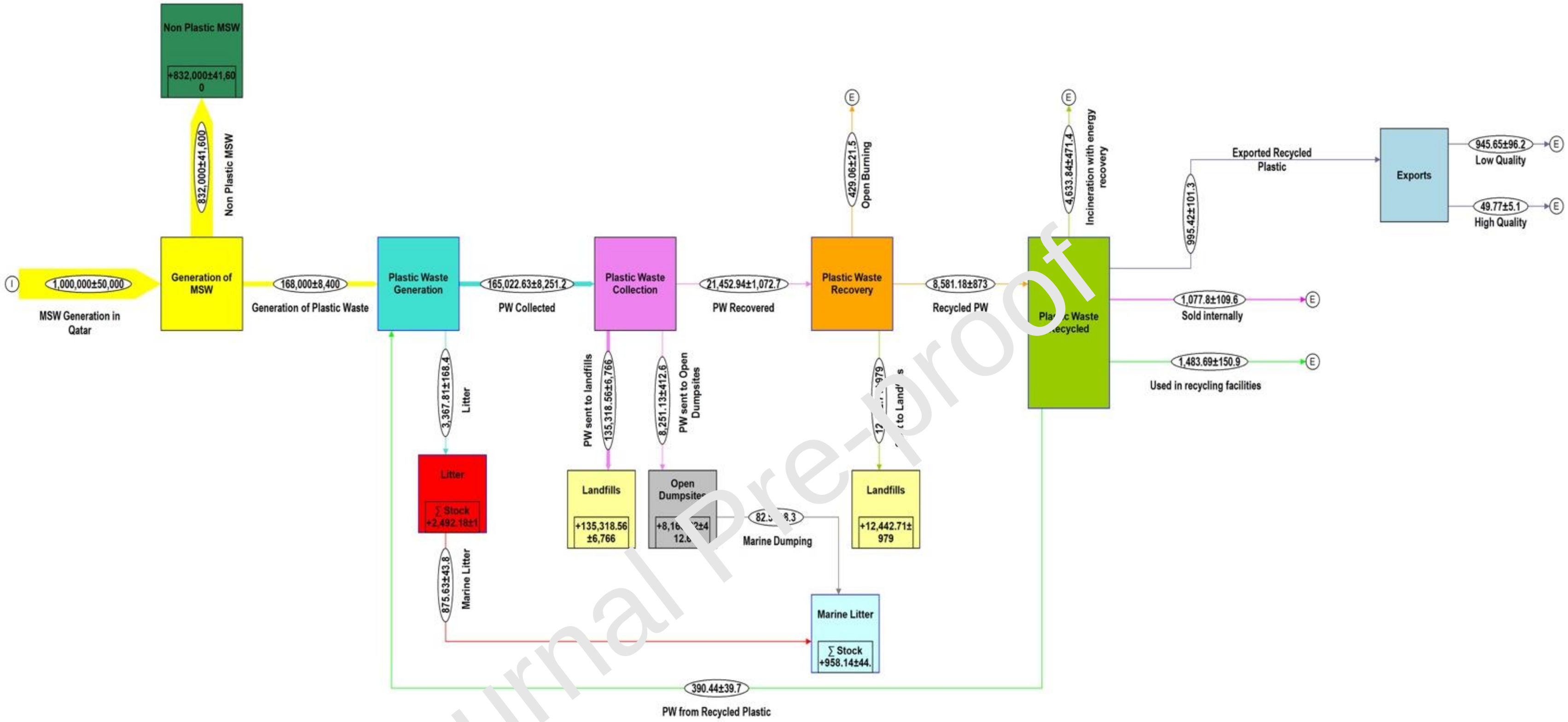

Figure 4. MFD of plastic waste in Qatar for the year 2017

Qatar has a relatively high per capita waste generation, and this can be attributed to the rapid industrial development and urbanization, increase in population rates and high standards of living (Al-Maaded et al. 2012). Consequently, the plastic waste generation rates are, also, high in Qatar (16.8±5%) due to the increased dependency and demand for plastics, making the plastic industry extremely valuable to the economy of the state.

The most commonly produced plastic types are LLDPE and LDPE (22±5%), HDPE (21±5%), PP (19±5%), PVC (16±5%), PET (14±5%), PS (5±5%) and other polymer types (3±5%) (Hahladakis and Aljabri 2019). Roughly half of the produced plastic types are single use (47%); therefore, it can be suggested that Qatar has a high usage of plastics in packaging, plastic bags, microbeads, etc. This is important information to consider for decision and policy makers, in order to implement plastic minimization strategies to reduce single-use plastic due to their very short lifecycle and detrimental effects on the environment, once disposed.

Generated plastic waste is either collected or disposed of as litter. Only 2±5% of plastic waste in Qatar is littered, 74±5% of which has been allocated in land litter and 26±5% in marine litter (Ghayebzadeh et al. 2020). According to our calculations and assumptions in STAN software, 98% of the plastic waste is collected and is either sent to landfills, open dumpsites or are recovered. The availability of land in Qatar and the low cost of landfilling makes it the predominant method of disposal in the State (Bello 2018), despite the global advances that have been made in the recycling industry. The collected waste is discharged at different stations around the country, from where 82±5% is sent to the landfills. Qatar currently has three landfills: Umm Al-Afai, for receiving bulky and domestic waste, Rawda Rashed oriented for C&D waste and Al-Krana for sewage wastes (Hahladakis and Aljabri 2019). When assigning the flow for open dumpsites, an inconsistency was revealed in literature. (Ghayebzadeh et al. 2020) reported that all plastic waste in Qatar is adequately managed, in contrast to other countries in the Arabian Gulf region were solid waste management practices are done in poor conditions. Elsewhere, it has been reported that a fairly substantial fraction of MSW in the country is unregulated and ends up in open dumpsites (Al-Maaded et al. 2012). A possible explanation for this inconsistency in literature may be the difference in years. In 2012 it might be that properly regulated landfills were not established in Qatar; or that what constitutes a landfill (properly defined, restricted and controlled area) differs from one country/region to the other. As a result, only a small percentage of 5±5% was assigned for the open dumpsite flow in the MFD of Fig. 4. Consequently, it is expected that small amounts of plastics from these unregulated and uncontrolled open dumpsites will end up as litter in the marine environment as a result of wind movement, water runoff and leaching. Therefore, 1±10% was assigned to account for the plastics that will evidently reach the marine environment as marine dumping. However, it seems to be that new, sustainable waste management plans are being put into place in Qatar. For instance, a new center for Domestic Solid Waste Management (DSWM) was established by the government to launch and manage waste recycling units and integrated waste management facilities (Al-Maaded et al. 2012). The third flow from the plastic waste collection is the plastic waste recovery. In the State, it is estimated that 14±5% of plastic waste is recovered (Hahladakis and Aljabri 2019), with the intention either to be recycled, landfilled or incinerated (with or without energy recovery). The percentage of recovered plastic waste that is openly burned was assumed to be approx. 2±5%. This assumption was made based on a news article published by “lusailnews”, where it was stated that waste is presented to private sector companies, of which include recycling factories, through bids and the rest of it is burned (Bediwy 2020).

3.2.2 Material Flow Analysis of Marine Plastic Waste in Qatar

Based on the findings of (Ghayebzadeh et al. 2020), the flow of plastic marine litter into the Arabian Gulf around the coast of Qatar was predicted to be around 875 tonnes per year. Compared with the input of plastics into the gulf by other countries in the region, Qatar had a fairly low number, and this is accredited to the fact that plastic input into Qatar's marine waters is well regulated, so waste is only dumped in sites approved by the Ministry of Municipality and Environment. The distribution of plastics that do reach the marine environment is demonstrated in Fig. 5. Fig. 5a shows the different shapes of plastics identified along the East Coast of Qatar.

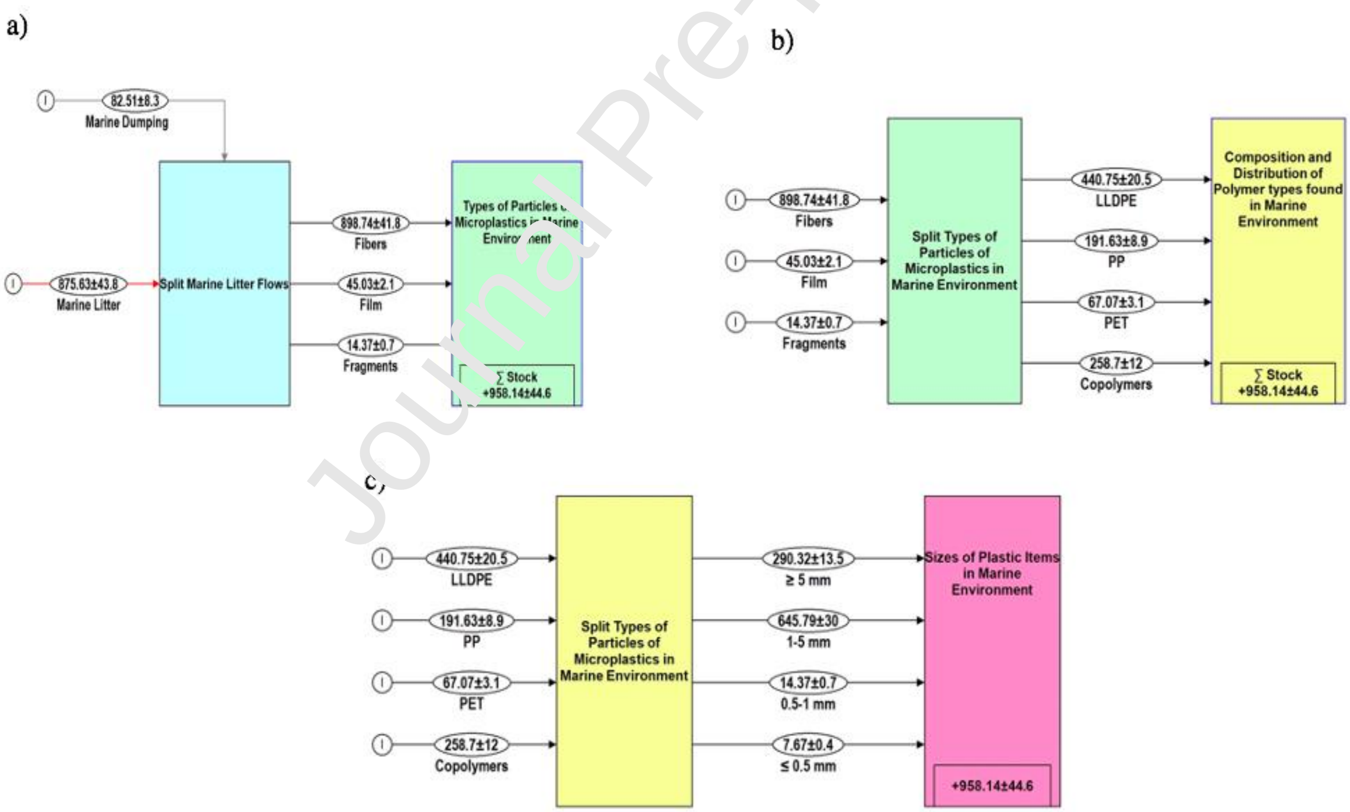

Figure 5. MFD of the marine litter subsystem in Qatar with regards to: (a) types of microplastic particles, (b) polymer types and (c) plastic item sizes

The most abundant was fiber plastics which accounted for 93.8±4.6% of the total plastics found, followed by film (4.7±4.6%) and fragments (1.5±4.8%), as was deduced by (Abayomi et al. 2017). This finding broadly supports the work of other studies conducted in the region, where it was found that fibers were, also, ubiquitous in the marine environment and displayed considerable spatial variation. The reason for this may be due to the fragmentation of abandoned fishing lines and nets as a result of fishing activities, likely being a main source of fiber input into the water (Abayomi et al. 2017). Another theory is that fibers may be introduced into the marine environment from sewage discharges as a consequence of washing synthetic clothes, however this is unlikely given that only 0.2% of sewage is discharged into the sea (Abayomi et al. 2017). Films and fragments were not as abundant and did not show the same spatial variation that fibers had.

Fig. 5b displays the different types of polymers detected in Qatar's marine environment. According to the findings of (Abayomi et al. 2017), it can be assumed that the most prevalent polymer type is LDPE (46±4.7%), followed by PP and LDPE copolymers (27±4.6%), PP (20±4.6%) and PET (7±4.6%). This is expected since the abundant polymer types in marine waters are used in single-use packaging which corroborates with the findings about types of plastic produced in Qatar.

As for the plastic sizes, it is clear from Fig. 5c that the dominant plastics found in Qatar's marine environment are large MPs (1-5mm), representing 67.4±4.6% of the total plastics. In turn, mesoplastics (≥ 5 mm) accounted for 30.3±4.7%, followed by smaller MPs (0.5–1 mm) which were only present in small amounts (approx. 1.5±4.9%) and lastly, the smallest MPs

(≤ 0.5 mm) accounted only for 0.8±5.2% (Abayomi et al. 2017). These findings are consistent with the studies that have been carried out in the Arabian Gulf to investigate the nature of plastics in the region (see Fig. 2).

In general, the quantification of plastics in the marine environment is challenging due to the magnitude of the sampling area and the ambiguous nature of the collected samples. In addition, the inputs and outputs are unclear due to the dynamics occurring in our natural environment (winds, etc.) and even more in the sea (currents, etc.).

3.2.3 Material Flow Analysis of Recovery Process subsystem in Qatar

Recovery processes in Qatar account for 14% of the total plastic waste collected. The most commonly recovered plastics in the State, shown in Fig. 6, are LLDPE and LDPE accounting for 55±5% of the total recovered plastics, whereas HDPE for 25±5%, PP (15±5%) and other polymer types (5±5%) (Hahladakis and Aljabri 2019). This may be explained by the plastic's tensile strength, where it decreases only by a small value from the pure material, making it highly recyclable (Meran et al. 2008). PET is not currently recycled in Qatar, however there are new initiatives taking place in Twyla Recycling company where PET bottles are recovered to produce sheets (Hahladakis and Aljabri 2019), and innovative methods are undertaken in Doha Plastic company to "close the loop" on PET bottles.

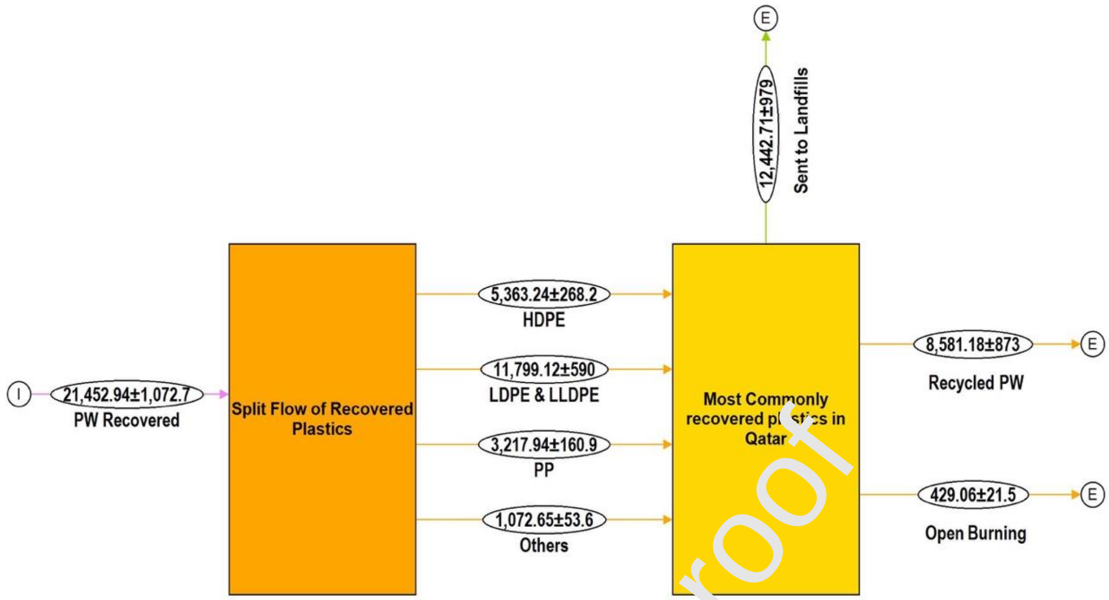

Figure 6. MFD of the recovery subsystem in Qatar: commonly recovered and recycled plastics

As reported by the Ministry of Commerce and Industry in Qatar, about 15 companies carry out plastic recycling activities, generating a wide range of plastic products such as plastic granules and plastic bags (MOCI 2017). Based on this information, 40% of recovered plastics are assumed to be recycled, amounting to 8.6±0.873 kt of recycled material. The predominately used methods of recycling are downcycling processes; and as is the case for the Arabian Gulf region, Qatar is no different. Downcycling processes can be divided into two approaches, 1) mechanical recycling pathways, which includes different methods such as shredding, drying or injection molding, or 2) chemical recycling pathways, such as pyrolysis gasification and refinery-based processes. In Qatar, the main motivation for recycling programs is the mechanical recycling of plastic waste (Al-Maaded et al. 2012), and so a 75±10% of the downcycling flow is assigned to mechanical recycling pathways.

4. Future Initiatives in Qatar: A Hope for the Future

Although plastic waste management practices in Qatar are not as comprehensive and fully established as compared to other countries in the world, the country has been making significant improvement regarding environmental sustainability. As part of the QNV2030, Qatar is aiming to achieve unity between economic growth, social development and environmental protection (GSDP 2008). To achieve this goal, it is necessary to spread environmental awareness in the public by establishing advanced environmental institutions, fund environmental research, create a legal system that protects the environment and participate in the international efforts to mitigate climate change effects; all of which are currently implemented in Qatar.

In accordance with this vision, several innovative ways to recycle plastics, using the circular economy concept, are being explored in the country. This method is largely dependent on using chemical recycling pathways to transform the plastic material back into its building blocks, and to keep revolving the materials inside the chemical cycle for the longest period of time. A crucial aspect of the circular economy model is the segregation of waste based on their respective materials. However, the major challenge that Qatar is facing concerns the recycling and collection methodologies and strategies. The needed technology to segregate waste to their individual components of the same type, in a scalable and automated way, is not available in the State and not enough awareness is spread throughout the public to segregate waste on their own. Therefore, this model still remains a challenge, however clear efforts are being made towards this initiative because of the sustainability it offers, both economically and environmentally.

Closed loop recycling is seldom implemented in Qatar due to the infeasibility of the method, previously mentioned in the study. However, Doha Plastic's engineers confirmed that the company is looking into recycling 20 tons of PET bottles a day using the "closed loop" method, starting 2022. Plans are, also, put into place to increase recycling rates and plastic capacity in the company by next year, in order to recycle 80 tons/d, a massive increase from the current 20 tons a day target.

Therefore, it is clear that Qatar has an interest in the development and enhancement of plastic recycling and the implementation of appropriate solid waste management strategies, with the intention to increase recycling rates in the country and reduce plastic waste input into landfills.

5. Recommendations

These findings suggest several courses of action for policy and decision makers in the GCC area, in order to achieve lower plastic waste generation rates and mitigate their adverse effects on the terrestrial and marine environment. One of the most valuable options for restoring the seas is reducing plastic litter inputs through efficient source separation-reduction and a proper waste management infrastructure. The implementation of an integrated waste management system that focuses on the four R's hierarchy (reduce, reuse, recycle, and recover) would be ideal. Plastic use can be minimized at the manufacturing level by employing alternatively, recycled and/or biodegradable materials. Other actions may include limiting the number of additives used in the polymers to enhance their properties, improving the design of products to enable better recyclability of plastics, increase products' lifecycle, allow repair and reuse and promote downcycling. Banning single-use plastics will, also, have a considerable effect on the generation of plastic waste.

For instance, countries around the world have taken several initiatives to mitigate the plastic waste problem. In an attempt to minimize the production of plastic, Taiwan has introduced the "Plastic Restriction Policy" where a ban on plastic bags was enforced (Prata et al. 2019); in Canada the federal government banned the use of microbeads in cosmetics and toiletries; and in England and Wales, a fee of five pence was imposed on plastic bags, dropping the use of plastic bags by 85% and 96% respectively (Walker and Xanthos 2018, Xanthos and Walker 2017). Consequently, many countries have steadily adopted the "plastic ban" initiative, such as South Africa, Bangladesh and India, and relative fees have been imposed elsewhere, too, (e.g. in Ireland) (Xanthos and Walker 2017). It has also been found that countries with a higher budget investment in waste management, generally have less litter on the coast and subsequently in the marine environment, as is the case for Australia (Prata et al. 2019). Clean-up activities are, also, suggested as mitigation methods and awareness-raising initiatives.

6. Conclusions

The present work mainly aimed at delineating and mapping the plastic waste generated in the GCC region (focusing on Qatar, separately) and to give specific attention on the plastic waste entering the marine environment of the Arabian Gulf. It was found that approximately 1.6 Mt ± 82 Kt and 168 kt ± 8.4 Kt of plastic waste is generated in the GCC and in Qatar, respectively. Roughly 2.8 kt ± 14 kt and 0.87 kt ± 0.044 kt are introduced every year into the marine environment of the Arabian Gulf region and Qatar, respectively. The rapid development of the area, population increase and the vastly improved lifestyle, all contribute to a rather increased generation of plastic waste, some of which, ultimately, ends up in the marine environment through direct littering, anthropogenic derived activities or sewage effluents.

Considerably more work is needed to determine the flow of plastic waste after collection in the region, and the impact of the arid climatic conditions on plastic fragmentation as well, which can easily increase the amount of micro and nano-plastics found in the Arabian Gulf. Several gaps in literature, concerning the rate of degradation reactions of MPs in the marine environment, have been identified, as well.

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CRediT author statement

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Graphical abstract

Highlights

- A mapping of the plastic waste status in the Arabian Gulf region was performed.
- Material flow diagrams (using systems and subsystems) were built using STAN software.
- Marine plastic types and sizes in the Gulf Region and in Qatar were further analysed.
- Polyethylene is the most common polymer type found in the Arabian Gulf and Qatar.
- Recycling efforts in the Arabian Gulf region are either lacking or at primary stage.

Declaration of interests

☒ The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

☐The authors declare the following financial interests/personal relationships which may be considered as potential competing interests:

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Danah Ibrahim Jaser Alagha: data curation, investigation, writing original draft

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