A Call for Digital Transformation in the Marine Environmental Protection Sector: A case for marine plastic litter pollution monitoring

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ABSTRACT

As one of the top contributors of marine plastic litter in the world's oceans, the Philippines, having recognized the seriousness of this problem has adopted a National Plan of Action for the Prevention, Reduction, and Management of Marine Litter (NPOA-ML). One of the initial steps of the NPOA-ML is to perform marine litter baselining in identifying the extent of the plastics pollution problem in the environment. Further, recent stakeholder engagements have identified that two of the priority research areas – 'marine environmental protection,' and 'digital transformation' – in the Philippine maritime sector are aligned with the establishment of baseline data for marine litter. Provided that there are local initiatives in consolidating the available plastics data, this study presents a framework for the digital transformation of plastics data in defining the extent of marine plastics pollution in the country. Briefly, the framework considers the digitization of plastics data from land and sea-based sources, then coupled with the appropriate mechanistic model (i.e., process models) that serves as a backbone for digitalization. Consequently, the direction towards the development of a technological artifact, when using the said framework as a basis, can serve as a holistic risk-assessment tool for the crafting of reduction, control, and mitigation strategies by stakeholders at various levels in the national government.

Keywords: marine plastics pollution; digital transformation; digitization; digitalization; marine environmental protection

1. INTRODUCTION

The Philippines is one of the countries that has an extensive biodiversity and is considered to have the fifth longest coastline in the world [1]. The archipelagic-maritime context of the country has been accompanied by rapid economic growth, urbanization, and globalization, which in turn has generated a wide range of environmental effects that exposed majority of the population to climate change impacts (*e.g.,* extreme weather events, severe flooding, etc.) [2]. Along with this, the country has also been identified as one of the major contributors of marine plastics to the ocean with ~0.75 million tons of plastic waste annually discharged to the open sea; which is 6% of the total estimated marine plastics pollution to the world's oceans [3]. Despite being identified as a major plastics pollution contributor, there are limited research efforts in trying to define the marine plastics problem in the country; aside from the early reports of the presence of macroplastics in the environment and microplastics in marine biota and with the first call for marine plastics research that has been made in 2018 [4-13]. As the marine litter[1] problem has been deemed significant, that it needs to be addressed on a national level, the government has adopted the National Plan of Action for the Prevention, Reduction, and Management of Marine

[1] https://seaknowledgebank.net/e-library/philippines-national-plan-action-prevention-reduction-and-management-marine-litter. Defined marine litter as "any persistent manufactured or processed solid material discarded, disposed of, or abandoned in the marine and coastal environment. It consists of items that have been made or used by people and deliberately discarded into the sea, rivers, and beaches; brought indirectly to the sea with rivers, sewage, storm water or winds; or accidentally lost, including materials lost at sea in bad weather." https://wedocs.unep.org/handle/20.500.11822/7824. The UNEP 2009 report is the basis for the definition of marine litter.

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Litter (NPOA-ML)[2] which has the overarching goal of 'zero waste to Philippine waters by 2040' to support the vision of 'a Philippines free of marine litter through shared responsibility, accountability, and participatory governance. The strategies of the NPOA-ML are based on the following guiding principles: science and knowledge based approaches for the implementation of ecosystem-based interventions that incorporate precautionary, prevention, and polluter-pays principles; whole-of-economy approach that includes stakeholder involvement and public participation provided with operational support and continuous funding of activities; and the doability, applicability, and appropriateness of a phased-approach to strategic program implementation in the Philippine setting.[3] One of the strategies of the NPOA-ML is the national marine litter baselining – where the extent of marine litter pollution in our country is to be determined such that it can provide implementers and decision-makers necessary information from which strategic interventions can be crafted. As such, there is a need to collectively focus research efforts in generating baseline data as this is the first step in science-based policymaking processes.[4] Although marine litter encompasses a variety of solid waste in the environment, this study however focuses on marine plastic litter (MPL) as local literature and research efforts are currently lacking and that it is highly relevant to the recently passed 'Extended Producers Responsibility (EPR)[5] legislation [2]. Thus, with the aim to provide guidance on defining the marine plastics pollution problem in the country, this study attempts to present a framework for the digital transformation of current plastics baseline data as 'marine environmental protection,' and 'digital transformation' have been considered as top priorities in the research and development agenda of the Philippine Maritime Sector [14].

2. PLASTIC RESEARCH IN THE PHILIPPINES

Prior to the research call initiated by Abreo [4] last 2018, plastics ingestion by marine biota – green sea turtle [15], beaked whales [16], and sardines [17] – has been reported in the literature. Then came studies that highlight efforts regarding the characterization of plastics (both macro and micro) in the environment – beaches (*i.e.,* Macajalar Bay in Cagayan de Oro [18], Talim Bay in Batangas [13], Mayo Bay in Davao Oriental [19]), rivers (*i.e.,* Pasig River in Manila [20], Matina River in Davao City [21]), seagrass beds in Iligan City [22], and mangrove forests (*i.e.,* Pujada Bay in Davao Oriental [12], coastal areas of Puerto Princesa Palawan [23], and coastal mangrove areas around Cebu Island [24]). Additionally, microplastics presence in marine biota – oysters and selected fish species in Bombong Estuary Batangas [25], selected fish species in Eastern Visayas [26], whalesharks [27], and rabbitfish [11] – has been reported. These reports regarding the presence of macro and microplastics in the environment constitute the baseline data that we have on 'how much' plastics have gone to the environment and its corresponding ecosystems.

However, the presence of plastics in our environment and ecosystem only addresses the 'how much' part of the problem. The alarming part is that there is limited research on determining 'how fast' plastics are discharged to the environment. Previous estimates on the amount of plastics discharged into the world's oceans relied only on reported country-scale statistics on municipal waste generation and that a fraction of which is assumed to have reached the ocean along with river emissions – that is a function of rainfall and plastic waste generation [28-30]. This basis could somehow lead to the overestimation of plastic inputs into the ocean and that dynamics of plastics release into the environment are vaguely known. In determining the dynamics of the fate and transport of marine litter, a global mass balance budget model has been proposed by Lebreton, et al. [31][6] – such that the key processes governing the fate of marine plastic litter based on field evidence are identified and incorporated – and that this mechanistic model serves as a guide to orient researchers in determining 'how fast' plastics are transported into the environment. The utilization pseudo-steady state compartmental material balance approach derived from the global mass balance model to determine the fate and transport of macroplastics in the coastal mangrove areas [32] and plastics transport between riverine mangrove and beach areas [33] has been demonstrated in the local context. Similarly, van Emmerik, et al. [8] estimated the plastic fluxes in three main rivers of Manila – Meycauayan, Tullahan, and Pasig – via an expanded visual counting method which gave insights to the potential sources, sinks, and pathways of marine plastics pollution in Manila. Cruz and Shimozono [7] further explored the transport of plastic litter within the Manila Bay using particle tracking model simulation approaches; where plastic litter particles tend to accumulate along the northeastern coastline of the bay during the southwest monsoon, and that litter particles tend to travel outside the bay during the northeast monsoon.

Overall, the local baseline data from the cited literature show that there is a need to harmonize efforts in the generation of said data for an island-wide scale and then integrating it for national-scale to properly account the generation, mismanagement, and the fate and transport of plastic waste into the environment, considering the archipelagic configuration of the country. Moreover, the curation of datasets that come from R&D initiatives and creating a database for such is a laborious task considering the lack of harmonized systems and protocols for digital transformation.

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[2] In reference to the following memorandum circulars and resolutions of the Department of Natural Resources (DENR) that adopted the NPOA-ML: DENR Memorandum Circular 2021-10 and NSWMC Resolution No. 1441, Series of 2021

[3] See Footnote 1 for the NPOA-ML basis document. The twelve (12) key government agencies that are involved in the institutional arrangements of the NPOA-ML are the following: Department of Natural Resources (DENR) as the overall head of the high-level multi-stakeholder body; Department of Science and Technology (DOST); National Economic and Development Authority (NEDA); National Solid Waste Management Commission (NSWMC); Department of Interior and Local Government (DILG): Local Government Units (LGUs); National Coast Watch Center (NCWC); Department of Transportation (DOTr); Department of Agriculture Bureau of Fisheries and Aquatic Resources (DA-BFAR); Department of Education (DepED); Office of the Press Secretary (OPS) / Philippine Information Agency (PIA); and the Department of Budget and Management (DBM).

[4] See Footnote 1. Part of the institutional arrangements of the NPOA-ML is that the DOST and DENR will take the lead in the establishment of science and evidence-based baseline information on marine litter hand-in-hand with stakeholders from Academe (SUCs, HEIs), Research Institutes and other development cooperation agencies. This strategy consists of four action points namely: i) Development of the National Research Framework and Program for the Monitoring and Assessment of Marine Litter; ii) Standardize methodology and appropriate data collection system for marine litter information in the Philippines; iii) Carry out a national baseline assessment on waste leakage and accumulation of litter in the marine environment; iv) Make science- and evidence-base and vetted information on national marine litter baselines available and accessible, including spatial visualization and building networks for dissemination

[5] http://legacy.senate.gov.ph/republic_acts/ra%2011898.pdf. Extended Producer Responsibility Act of 2022. Where the legislation has lapsed into law and that there is a need of science- and evidence-based approaches in crafting its corresponding implementing rules and regulations (IRR). https://emb.gov.ph/wp-content/uploads/2022/11/Vers-11A-Format-1-EPR-Draft-IRR.pdf. It should be noted that the draft of the IRR based on a series of public consultations all throughout the archipelago and was crafted based on the limited baseline data and research studies at the time of its crafting.

[6] This process model based on a global ocean surface mass balance model considers the following mechanisms: i) emission of plastics from land-to-sea and vice versa, ii) stranding settling and release in the seabed, iii) plastics transport mechanisms, iv) degradation of macroplastics to microplastics along the pathways.

3. DIGITAL TRANSFORMATION FOR MARINE PLASTICS POLLUTION RESEARCH

The implementation and use of 'digital technology' that causes fundamental changes in traditional business practices is referred to as 'digital transformation (DT)'. There are two phases prior to the realization of DT. The first phase towards DT is 'digitization,' a process concerned of making information available and accessible in a digital format. Then followed by the 'digitalization' phase where it is a process of increasing the level of automation in processes using digital technologies. [34] In the context of marine plastics research, the DT focused in this study takes the form of adopting digital technologies that aim to establish the baseline data of the extent of the marine plastics pollution in the country such that its further development would lead to technologies that generate intervention measures that reduce, control, and mitigate the marine plastics pollution. Then, digitization focuses on the conversion of locally available plastics data into a digital form with respect to corresponding technologies for such (*e.g.,* remote sensing, etc.). Subsequently, digitalization in this context looks at the utilization of process analytical technologies[7] that aims to establish the 'digital twin model[8]', that can provide a process description of the fate and transport of marine plastics to the environment [36, 38].In other words, the digital transformation in marine plastics research for this study refers to the utilization of digitization; process (*i.e.,* process model approaches), and data reconciliation and parameter estimation technologies to describe the extent of marine plastics pollution in the country – fate and transport of plastics in the environment.

Aside from determining the extent of marine plastics pollution in the Philippines – by answering the 'how much' and 'how fast' questions regarding the fate and transport of marine plastics litter into the environment and ecosystem – another concern is on having a holistic system which can integrate all the baseline data generated into a platform that is readily accessible for a wide range of stakeholders, that engage in decision-making processes for the reduction, control, and mitigation of marine plastics pollution throughout the country. A simplistic framework for having a holistic system for determining the extent of marine plastics pollution is shown in Figure 1 (which is a simplified version derived from the global mass balance budget model [31]), that provides an avenue for digital transformation with respect to the digitization and digitalization of plastics data to determine the marine plastics pollution extent. This framework considers plastic sources and receptors along with the types of data that can be obtained and digitized, along with the corresponding process models (based on material balance approaches) that serve as the backbone for digitalization of the digitized data.

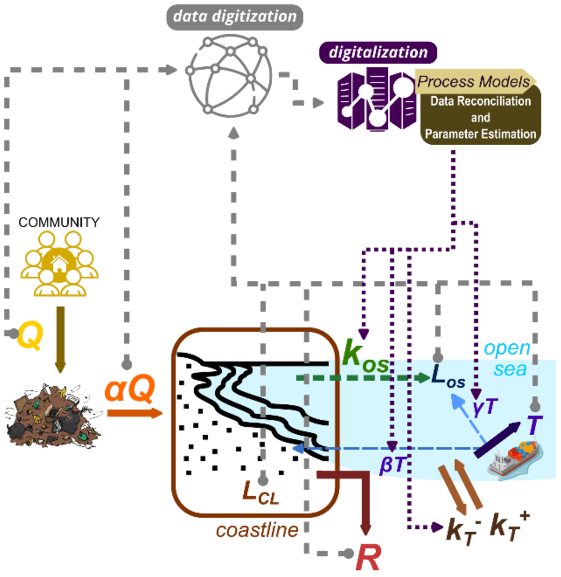


Figure 1. Simplistic framework for digital transformation in determining the extent of marine plastics pollution by using material balance-based process models along with data reconciliation and parameter estimation of the digitized data for the estimation of model parameters. Where variables in this framework are: community plastics waste generation, Q (in terms of tons/day); fraction of mismanaged waste from the community, α; plastic load in the coastline, L_{CL} (in terms of kg/m^2); pseudo-first order transport rate, k_{OS} (in terms of day^{-1}), which accounts for coastline to open sea transport; rate of removal of plastics from coastline via direct reduction measures, R (in terms of tons/day); plastic load in the open sea[9], L_{OS} (in terms of kg/m^2); plastics transported on ships as they pass by the coastline, T (in terms of tons/day); along with the fractions of T that is mismanaged and goes into the open sea, γ, and that goes back into the coastline, β; inter-site transport rate constants from other systems (i.e., municipality, or island), k_T^+ and k_T^-, respectively for incoming and outgoing plastics to and from the system.

The framework shown in Figure 1 identifies land- and sea-based sources of plastics data that undergoes data digitization; with the coastline and open sea[10] that as temporary sinks for a compartmentalized system (*i.e.,* island-scale). Then, the process of digitalization involves the input of digitized data to the process model (based on material balance approaches) coupled with data reconciliation and parameter estimation (DRPE) techniques; for

[7] See Simon, et al. [35]. Process Analytical Technology (PAT) is defined as a system for designing, analyzing, and controlling manufacturing processes through timely measurements (i.e., during processing) of critical quality and performance attributes. It should be highlighted that the analytical context of PAT can include the chemical, physical, microbiological, and mathematical analyses possibly conducted in an integrated manner. In the context of this study, the PATs considered are the mathematical modeling techniques in defining the fate and transport of plastics to the environment.

[8] See Lee, et al. [36]. The digital twin model is a virtual model of a process, product, or service. This pairing of the virtual and physical worlds allows analysis of data and monitoring of systems to head off problems before they even occur, prevent downtime, develop new opportunities and even plan for the future by using simulations. The digital twin of a target system enables understanding, learning, and reasoning, developed for part of or all of an entity's life cycle, delivering on specific use-cases to provide business or process improvement. Essential to the pairing of the virtual and physical worlds is the utilization of data reconciliation techniques in adjusting process measurements and parameters so that conservation laws and process constraints can be fulfilled. See Yang, et al. [37] on process data reconciliation

[9] Open sea plastics measurement can be sourced from direct surface plastics measurement and recovery efforts or underwater cleanups. However, there is a lack of efforts in quantifying open sea plastics such that it is a challenge to establish initial conditions of the open sea plastic load. Nonetheless, plastics data from underwater cleanups can be utilized to estimate open sea plastic load provided that it will neglect the phenomenon of plastics sinking under the ocean.

[10] See Tabañag, et al. [32]. In establishing the compartmental balances for plastics transport through mangroves, it was assumed that open sea transfer back to the mangroves is neglected since plastic load in the open sea can be considered too small with respect to the open sea area (when expressed in terms of plastic mass per unit area). Also, supporting this assumption is the lack of local data for the plastics measurement in the open sea as these would require the use of trawls attached to vessels and that there have been no reported initiatives in the country that collected plastics data on sea. See https://theoceancleanup.com/dashboard/#. The Ocean Cleanup Foundation, a non-profit organization founded last 2013, have deployed cleanup systems that intercepts plastics in rivers before it reaches the oceans and also remove the plastics that are already out in the open sea. Data collected from these cleanup systems are uploaded and freely accessible in their website.

the estimation of rate constants and waste fractions, and plastics measurement adjustment (in cases for automated techniques in plastics monitoring) in order to fulfill the mass conservation laws. The flow of data considering the digital transformation framework can lead to the real-time monitoring and determination of the dynamic nature of open sea plastics transport, along with the fractions of plastics waste from maritime traffic; as shown in the gray and purple flows in Figure 1. Moreover, the following sub-sections discuss on the digitization and digitalization aspects of the digital transformation interventions described in Figure 1.

3.1. Digitization of Plastics Load Data

Plastics waste characterization data that are obtained via representative sampling or direct intervention measures (i.e., cleanups) can be categorized in terms of land and sea-based sources with respect to the system described in Figure 1. The nature of these data along with their accessibility is discussed in the next few paragraphs.

3.1.1. Land-based sources of plastics data

One of the major sources of plastics waste in the environment is the community and part of the country's initiatives in addressing ecological waste disposal is solid waste management (SWM) that is implemented and enforced at the local government unit (LGU) levels [11]. In the implementation of the solid waste management programs at the LGU-level, LGUs are required to prepare ten-year SWM plans. Part of the tasks in preparing the SWM plans is the conduct of the activity called the Waste Analysis and Characterization Study (WACS). WACS looks at both ends of the waste streams – waste generation at source, and waste 'at the end of the pipe' (*i.e.,* waste that is collected and brought to the disposal area). Then the WACS also provides an estimate of the 'waste that leaks out of the stream' or 'unaccounted waste' – waste that are uncollected and thus disposed to the environment. [39] As such, the municipal plastic waste generation Q and fraction of mismanaged waste α can be derived from the WACS of each corresponding LGUs. However, WACS data is not freely available to the public and that proper correspondence is necessary when requesting for its access[12]. Aside from the mandatory WACS in LGUs that are used as basis for the solid waste management plans, WACS has also been used as a tool in research that tackle effective waste management strategies that incorporate novel waste recycling technologies [40-44].

With respect to direct intervention efforts to reduce plastic litter in the environment, the country's participation to International Coastal Cleanups (ICC) has been mobilizing citizen-science volunteers to remove trash from beaches and waterways throughout the country while instilling the awareness of the marine debris issue and a sense of stewardship for natural resources[13]. The country-wide cleanup efforts during the ICC month involve the participation of multiple stakeholders from the National Government Agencies (NGAs), Non-Government Organizations (NGOs), Civil Society Organizations (CSOs), Professional Organizations (Pos), Academe, Local Government Units (LGUs), and Development Organizations (DOs)[14]. In the recent cleanup activities, the ICC along with relevant stakeholders have promoted the use of the Clean Swell ® App to easily record each item of trash being collected during cleanups; and as part of long-lasting solutions for the problem of marine plastics impact to the ocean[15]. The digitized trash collection data during ICC events are freely accessible on the Trash Information and Data for Education and Solutions (TIDES) database[16]. Although the country has numerous volunteers during the ICC-Ph events, the essence of citizen-science data collection practice is somehow neglected and that trash data in the TIDES database is somehow underreported. Aside from the participation to ICC events, several NGAs, NGOs, and CSOs have made it a part of their mandates and functions to do monthly coastal cleanups within their respective areas of responsibility (AOR)[17]. However, the nature of data from these cleanup activities is similar to that of the municipal WACS data; available upon request and/or with proper correspondence.

3.1.2. Sea-based sources of plastics data

In contrast to land-based sources of plastics data, sea-based plastics data sources are rather limited as plastics monitoring activities (*i.e.*, regular cleanups) on sea require more resources (*i.e.*, the use of nets and trawls for sea surface plastics, and diving equipment for underwater plastics on coral reefs and seabed) than that of the land-based plastics monitoring. As a parallel activity to the land-based cleanups, underwater cleanup activities which usually is termed as 'Scubasurero.[18]' Unlike the land-based cleanups, participants in the scubasurero activities are certified divers from various organizations (*e.g.*, PCG, PCGA, PADI, diving clubs, etc.), and trash data collected from these cleanup initiatives are made available upon request from the PADI AWARE Project[19]. Consequently, Roman, et al. [45] have demonstrated the global analysis of land and seafloor plastics data from the ICC and Project AWARE databases. Although these initiatives are done all throughout the country, the comprehensiveness of the data collection process is not that extensive when compared to the ICC-based activities.

[11] Ecological Solid Waste Management Act of 2001 (R.A. 9003) and that this act is the primary accountability of LGUs within their respective jurisdictions as stipulated in the Local Government Code of 1991 (R.A. 7160)

[12] Freedom of Information (FOI) Executive Order No. 02 of 2016 (E.O. No. 2 of 2016)

[13] Proclamation No. 470, s.2003 'Declaring the third Saturday of September of each year as the International Coastal Cleanup Day (ICC) in observance of the global coastal clean-up celebrations).

[14] https://sites.google.com/site/iccphilippines; https://sites.google.com/site/coastalcleanuppcga/ – The ICC-Philippines is the National Coordinator with respect to the country-wide cleanup events. Along with the DENR and PCG-PCGA as the co-national cleanup coordinators from the NGA and NGO-CSOs, respectively. The national-level coordination of the ICC cleanup activities ensures that the plastics recovered and data collection from cleanup activities follow the ICC guidelines in terms of the methodologies for implementation and documentation. In addition, it is the Ocean Conservancy, a Washington-based NGO who is responsible for the worldwide coordination of the ICC

[15] https://oceanconservancy.org/trash-free-seas/international-coastal-cleanup/cleanswell/ - The Clean Swell ® App is a technological solution to replace the standard trash data forms that are accomplished manually by the activity coordinators.

[16] https://www.coastalcleanupdata.org/ - TIDES database is where citizen science data from cleanups are collected during ICC activities by Clean Swell ® users. Also, PCGA ICC-Ph coordinators who have opt to collect the trash data manually via the ICC's Ocean Trash Data Form are instructed to either submit the cleanup data to Ocean Conservancy or directly upload the trash data to the TIDES database.

[17] https://coastguard.gov.ph/index.php/transparency/about-us/mission-vision; https://mepcom.coastguard.gov.ph/transparency-seal/about-us/mandates-mission-and-vision/; https://pcgaaux.jblfmu.edu.ph/pcga-function-areas/; the Marine Environmental Protection Force (MEPFORCE) under the PCG's Marine Environmental Protection Command (MEPCOM), and the Auxiliary Squadrons of PCGA, the NGO-CSO counterpart of the PCG, have made monthly coastal cleanups as part of their regular mandates and functions at a country wide scale. However, the cleanup data from such regular activities are sparse as the 'data collection' component is not highlighted during the conduct of these activities

[18] https://www.diveagainstdebris.org/action/scubasurero – that means a group of divers or individual who voluntarily join the reef and coastal cleanup. The scubasurero initiative is also a part of the Dive Against Debris Specialty Course offered by the Professional Association of Diving Instructors (PADI)

[19] https://www.diveagainstdebris.org/ – The map resented in the dashboard represents the largest underwater citizen science database and movement for marine debris on the planet.

With respect to the sea-based waste management strategies, the institutional structure that used to coordinate the management of sea-based sources of waste is well organized despite limited policy support[20]. With this policy structure, the regulation of ship waste disposal is implemented through various executive and administrative orders of the relevant government agencies[21]. As a consequence of such regulations, all vessels are required to have a Garbage Record Book (GRB)[22]. The GRB is maintained and kept on board at all times with the following items recorded but not limited to: i) loss of fishing gears, ii) discharge of cargo residues, iii) discharge at port reception facilities, and iv) discharge of garbage at sea. Further, all garbage disposed by ships to port reception facilities or accredited garbage collectors are recorded to the GRB[23]. Therefore, data recorded in the GRB with respect to the plastic waste being recorded on-board and that of those from the port reception facilities or accredited garbage collectors can be utilized to trace the extent of plastics being discharged to the open sea. However, the accessibility of the GRB data depends upon proper correspondence with the relevant government organization, port waste reception facilities and designated shipping company representatives. While there is a concern regarding the practice of misreporting the information in the GRB, this can be addressed if the conventional way of manually filing and managing documents is transformed into a digital and online way of archiving such as that of a Centralized Document Processing and Support System (CeDoPSS) as discussed by Berdin, et al. [46]. This misreporting of GRB information also affects how the fraction of mismanaged plastic waste from ships are estimated via process modeling and this avenue is where blockchain technologies can be incorporated to ensure that process parameters are estimated appropriately [47-49].

3.1.3. Digitization Technologies for Plastics Monitoring

It should be noted that the land-based data that are locally available are collected on-field via representative sampling (in WACS), direct reduction measures (*i.e.,* cleanups), and experimental fieldwork that are part of research activities (as highlighted in Section 2). The nature of on-field data collection is resource-intensive due to its people, and process (*i.e.* collection methodology) requirements. Albeit that most of the people participating in direct reduction measures do so voluntarily.

In order to address these resource-intensive requirements in plastics field data collection, efforts on utilizing automated and AI-assisted methods have been demonstrated in literature. Briefly, Martínez-Vicente, et al. [50] have discussed the role of a satellite remote sensing system (SRSS) in making a substantial contribution to determining the plastic debris mass balance. Specifically, they have provided a view on the definition of the observational (sampling) requirements for SRSS design with respect to the identified main processes that are relevant for marine plastics debris monitoring. Active sensor techniques have also been included to incorporate passive radiometric methods for plastics identification. Lastly, it was highlighted that there is a differentiation and overlap in terms of temporal, spatial, and spectral requirements for the remote sensing of plastics for both land and coastal plastics monitoring. [50] Consequently, land-based plastics monitoring using an unmanned aerial vehicle (UAV), in a riverine system, has been demonstrated by Geraeds, et al. [51]. It was found out that plastics measurements via UAVs and field data collection show similar patterns and variations in terms of the spatiotemporal distribution of plastics in the Klang River, Malaysia. This shows that UAV-based monitoring methods are promising alternatives to the current fieldwork approaches for monitoring plastics distribution and transport; especially in remote and inaccessible areas. [51] Moving to sea-based plastics monitoring, de Vries, et al. [52] have demonstrated the utilization of vessel on-board cameras (GoPro®) coupled with artificial intelligence (AI) techniques for object-detection in the remote sensing of floating plastic debris. The floating macroplastic loads that were estimated by combining the object-detection solution algorithm with the bulk processing of optical data have been revealed to be consistent with the plastic loads predicted by global plastic dispersal models. This automated method for macroplastics monitoring provides an alternative to the use of manta trawls[24]. [52]

3.2. Process Modeling for the Digitalization of Plastics Data

In consideration to the possibility of completely digitizing the plastics data presented in Section 3.1, we have to look into the nature of how such data will be processed in order to mechanistically determine the fate and transport of plastics from land to sea, and to properly define and address the marine plastics pollution problem. As we move towards the penultimate goal of developing a tiered risk assessment tool or technological solution for marine plastics pollution, appropriate mechanistic models with respect to the available data are required. Such mechanistic process models that describe the fate and transport of plastics have been thoroughly discussed by Kooi, et al. [53]. Briefly, mechanistic models for plastics fate and transport have been categorized into the following: i) Emission-Based Mass Flow Modeling ,ii) Global River Models, iii) Multimedia modeling, and iv) Spatiotemporally Explicit models. These models are presented in the order of their resolution (*i.e.,* space-time resolution). In essence, plastic fate and transport models are built upon existing transport models that simulate other types of particles (or contaminants) such that said models incorporate the plastics-specific parameters and characteristics. It is worthy to note that the first models developed for plastics transport have ranged from mass-balance point-emission models to spatiotemporally explicit models; and that these models have not been calibrated due to the lack of data. [53] Thus, holistic plastics measurement campaigns that account plastics waste in the environment along with the standardization of analysis methods that would lead to comprehensive baseline data collection are definitely necessary for utilization of high-resolution models. Along with the utilization of process models based on material balance approaches, fate and transport parameters incorporated in the process model are determined via the coupling of data reconciliation and parameter estimation (DRPE) techniques[25] ranging from the simple data (via least squares method) to dynamic data regression. This is to reconcile the land- and sea-based plastics data and estimate the transport rate parameters in order to fulfill the mass conservation law. Aside from closing the mass balances via data regression, gross error detection with data reconciliation can also address the seemingly disconnected or sparse plastic load data sets. [37, 54, 55]

[20] Presidential Decree No. 979 or the Marine Pollution Decree of 1976. The policies for marine pollution that follows after PD 979 are excerpts of larger legislations such as Sec. 48 of RA 9003 and Sec. 27 of the RA 9275. This is then further supplemented by international agreements such as the International Convention for the Prevention of Marine Pollution from Ships (MARPOL).

[21] Key agencies that are responsible for the said policy structure are: the Philippine Ports Authority (PPA), the PCG, and the Maritime Industry Authority (MARINA) of the Department of Transportation (DOTr).

[22] that is duly registered at the PCG – Marine Environmental Protection Command (MEPCOM) – and monitored regularly during a vessel's MARPOL inspection

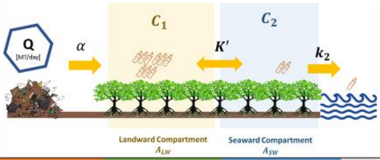
[23] PCG Memorandum Circular 07-14

[24] See Footnote 10, https://theoceancleanup.com/dashboard/# – On the described cleanup systems that remove floating plastics waste in the open sea which makes use of manta trawls for capturing said waste.

[25] See Footnote 8 Yang, et al. [37]. On the process data reconciliation using mass and energy balances for industrial processes.

The application of pseudo-steady state compartmental material balance approach coupled with DRPE has been first demonstrated locally by Tabañag, et al. [32] in understanding the macroplastics transport in coastal mangrove areas of Cebu Island as shown in Figure 2. In establishing the model, mismanaged plastics from the coastal communities are transported into the landward and seaward compartments of the mangrove area where they are temporarily retained, and then discharged into the open sea. Plastic load data in the landward (C_1) and seaward (C_2) compartments are obtained from fieldwork sampling. These then were inputted into the material balance model[26], as shown in Figure 2B. Then, the fraction of mismanaged waste, α; along with the mangrove retention and open sea transport rate constants are determined via parameter estimation using spreadsheet programming [56]. Results have shown that the coastal mangrove areas for the entire Cebu Island likely transports macroplastics into the open sea ~three (3) times faster than it is retained in the mangroves (in reference to the mangrove retention parameter value of 0.32) and that the island discharges approximately ~17 tons of plastics per day into its surrounding waters as shown in Figure 2A.

A



Mangrove Area	MRP, ψ	K' [day^{-1}]	k_2 [day^{-1}]	Plastics to Open Sea [kg/day]
Cebu Island	0.32	0.17	0.54	16,787

Values of transport rate constants K' and k_2 are calculated at α=0.0315 (obtained via Excel Solver GRG nonlinear Optimization ®), where α is the fraction of discarded waste going into based from the range 1.7-4.6% reported by Leberton, et al., 2019, Scientific Reports

B

Material Balances at Compartment 1:

$$\frac{dM_1}{dt} = 0 = \boldsymbol{\alpha} \cdot Q + \boldsymbol{K'}[C_2 \cdot A_{SW} - C_1 \cdot A_{LW}]$$

Material Balance at Compartment 2:

$$\frac{dM_2}{dt} = 0 = \boldsymbol{K'}[C_1 \cdot A_{LW} - C_2 \cdot A_{SW}] - \boldsymbol{k_2} C_2 A_{SW}$$

Mangrove Retention Parameter:

$$\psi = \frac{K'}{k_2} = \frac{C_2 A_{SW}}{C_1 A_{LW} - C_2 A_{SW}}$$

Figure 2. Looking at the fate and transport of macroplastics in the coastal mangrove areas of Cebu Island. (A) Compartmental modeling approach for the transport of macroplastics in mangroves; and (B) its corresponding material balances and the mangrove retention parameter.

With minimal plastics data collection in the environment, the integration of simplistic process models coupled with DRPE of the digitized data in Section 3.1 can provide understanding and insights of the extent of the marine plastics problem in the country, specifically on its fate and transport mechanisms that are linked to the process models. This understanding of the fate and transport mechanisms of plastics into the environment can be enhanced by employing complex process models as discussed in this section. Consequently, the complexity of process models also requires comprehensive data collection along the plastics source, pathways, and receptors in the environment. When looking at the whole-country perspective, understanding the marine plastics at this scale would require the generation of plastics data from the municipal to island level, and integrating island-based generated data to fit the country-scale. Specifically, local island-scale data collection with respect to the Cebu Island mangrove areas [32] is to be improved to incorporate other mechanisms of plastics transport, and then replicated in other islands to produce island-specific datasets in order to generate the country-level profile for marine plastics pollution.

This digital transformation framework can then serve as a basis of a risk-assessment and decision-making tool development for the crafting of reduction, control, and mitigation strategies for addressing marine plastics pollution. In addition, this framework can be further improved when supplemented with AI-based technologies for the management strategies tailored for marine plastics litter pollution [57].

3.3. Current Efforts in Digital Transformation for Plastics Baselining Research in the Philippines

3.3.1. On digitization of plastics monitoring and data collection

In an effort to increase the country's local capacity for monitoring the plastics pollution problem in coastal and marine environments, the University of the Philippines – Marine Science Institute (UP-MSI) launched the PlastiCount Pilipinas project[27]. The said project focused on two approaches addressing the increased capacity for plastics pollution monitoring.

Firstly, it had the personnel from relevant national government agencies (NGA) and centers[28], undergo a series of workshops, lectures, and fieldwork in an attempt to establish concerted inter-agency efforts for the monitoring of macro and micro-plastics. Then, an intensive training program on traditional and advanced methodologies for Microplastics Quantification, Identification, and Biodegradation has been designed to capacitate early career scientists in doing plastics research. Specifically, the training is on the utilization of advanced methodologies such as the application of AI or 'machine learning' to automate the quantification and detection of macro[29] and micro[30]-plastics from obtained images.

Lastly, a PlastiCount Pilipinas portal[31] was created to collate data generated through the project, historical data from NGAs, and data generated from local research efforts and making it digitally available and accessible to the public. Further, there is a monitoring map that contains relevant information on plastic loads (macro and micro) throughout the country with the aim to communicate the gravity of the plastics problem along with the limited data that we have that serves as a baseline for the implementation of the strategic thrusts detailed in the NPOA-ML.

[26] Model basis and assumptions are as follows: The system for considered is the coastal mangrove area and its area is divided into two compartments as shown from the Figure 2A: landward and seaward compartments and that plastics are well-mixed in the said compartments. The model has zero-dimension spatial resolution and is a pseudo-steady state model, where the plastic loads entering the mangrove environment are assumed to be at steady-state such that the temporal dimension is removed. Additionally, the degradation of macroplastics into secondary microplastics is not accounted for in this model and the plastic litter entering the mangrove environment is assumed solely from terrestrial sources, which are the mismanaged plastic wastes of each municipality. [32]

[27] https://www.plasticount.ph/index.php/c_home/map - the official website of the PlastiCount Pilipinas Project that is funded by the Department of Science and Technology Grants-in-Aid Program (DOST-GIA), DOST-PCIEERD, and Science and Technology Action Nexus for Development (STAND) Framework implemented by the Japan Science and Technology Agency (JST), UK Research and Innovation (UKRI), and DOST.

[28] See. https://www.plasticount.ph/index.php/c_home/training_program. On the PlastiCount Training Program (PlastiCount-TP) – Where the relevant government agencies, whose representatives, participated in the series of workshops, lecture, and fieldworks are: PCG-MEPCOM, DENR attached agencies – Biodiversity Management Bureau (BMB), Environmental Management Bureau (EMB), and Ecosystem Research and Development Bureau (ERDB) –, and the Philippine Council for Industry Energy and Emerging Technology Research and Development (DOST-PCIEERD)

[29] Macroplastics images are obtained via the use of UAVs, a.k.a. drones

[30] Microplastics images are obtained via Fluorescence Microscopy with Nile Red ® Staining

[31] See Footnote 27. On the data being available digitally to interested stakeholders

3.3.2. On digital transformation: process modeling by using coastal cleanup data

In a subsequent work, Tabañag [33], has made use of the ICC data[32] to study the transport of macroplastics waste to the beach through a river system in selected sites of Cogon, Pardo, Cebu City, as shown in Figure 3, using the modeling approaches[33] described previously [32]. Plastic load data in the mangrove (C_1) and beach (C_2) areas (compartments) are obtained from the TIDES database[34], as shown in Figure 3A. These then were inputted into the material balance model[35]. Then, the fraction of mismanaged waste, α was assumed to have a value of 3.15%, as the average value of the reported ranges for α by Lebreton, et al. [31]. This assumption was made since WACS data is unavailable in the municipality where the study site is situated and also to resolve the underdeterminate nature of the compartmental material balances when α is considered as an unknown. The river transport and open sea rate constants are determined via spreadsheet programming to close the mass balances. It has been found out that for the selected riverine mangrove – beach system, as illustrated in Figure 3B, plastics are transported into the open sea ~five (5) times faster than they are transported via the river system to the beach (in reference to the river-beach transport parameter value of 0.18). In addition, the beach site discharges ~fifty-five (55) kg of plastics per day to the open sea with respect to the selected mangrove-beach system.

The utilization of simplistic compartmental modeling approaches with coastal cleanup data (which is digitally available and accessible online), is one of the first local attempts to demonstrate the application of the digital transformation framework described in this study to describe the mechanism of plastics transport between a riverine mangrove community and beach then to the open sea.

4. OUTLOOK

Although the marine plastics research in the country is at its nascent stage, our current initiatives in establishing the plastics baseline data is a testament of the seriousness of our nation to define and address the marine plastics pollution in our country. While country-level efforts to define the plastics pollution problem via material flow analysis (MFA) have been demonstrated in Austria [58] and Indonesia [59], the limitation to the MFA approach is that it only provides the quantity estimates of plastics distributed in the system and does not incorporate the transport mechanisms on how fast plastics are going and being degraded into the environment. As such, the utilization of mechanistic models (*i.e.*, process models) complement material flow analysis, including the Source-Pathway-Receptor (SPR)[36] modeling [60-62] approaches. In addition, the shift from on-site data collection to automated plastics monitoring workflows as one of the components of digital transformation augments the process modeling approaches that goes with the ease of handling and processing data in the digital environment. Acknowledging that the Philippines is at its initial stages of implementing national-level baselining studies, here we recognize that there is a need to collect, consolidate, curate, and digitize plastics data from various national government agencies, academe, non-government, civil society, developmental, and professional organizations. As efforts have already been taken to ensure concerted inter-agency efforts in plastics research, it should be highlighted that there is also a need for assessing the current capacity and thrusts when considering the feasibility of pushing for digital transformation in this field.

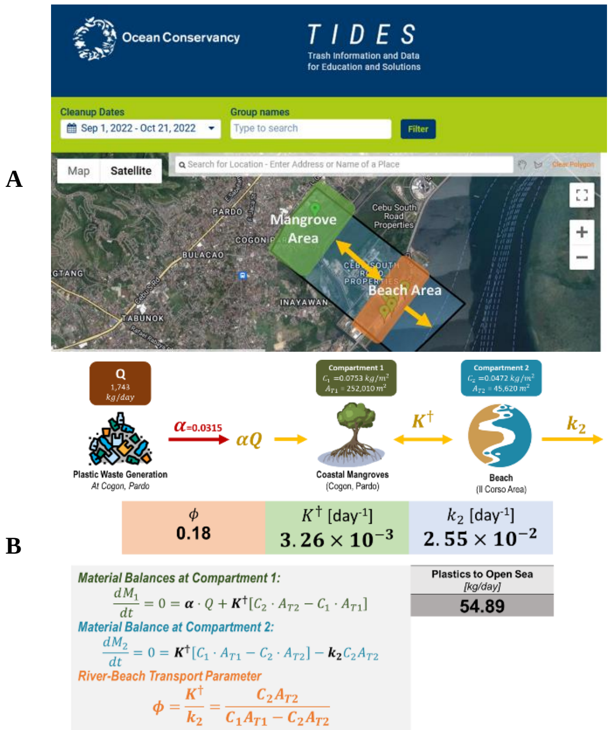


Figure 3. On the transport of macroplastics from a riverine mangrove community to the beach. (A) Coastal cleanup data for Cogon, Pardo (mangrove area) and Il Corso Lifemalls, Cebu City (beach area) as made available in the TIDES database. (B) Compartmental modeling approach for the transport of macroplastics in the riverine system to the beach and its corresponding material balances and the River-Beach transport parameter.

As such, the digital transformation framework presented in this study specifically tackles the coupling of digitized plastics data with appropriate process models and DRPE techniques, to realize digital transformation in plastics research. Research areas on the application of digital technologies in designing systems for data digitization, complex process models and DRPE approaches, and inclusion of multi-criteria decision analysis tools (MCDA) in plastics life cycle assessment (LCA) will lead to the development of a holistic risk-assessment tool for the crafting of reduction, control, and mitigation measures by stakeholders at various levels in the national government.

[32] The data were obtained from two simultaneous cleanup activities organized by the PCGA 219th CGAS in Bgy. Cogon, Pardo, Cebu City (Mangrove Area) and the other by the Philippine Institute of Chemical Engineers – Cebu Chapter (PIChE-Cebu) in the Il Corso Lifemalls, Cebu City (Beach Area) during the last ICC day celebration, 17 September 2022.

[33] See Footnote 26 on model assumptions. For this case, the mangrove transport rate K' has been replaced with the river transport rate, K

[34] See Footnote 16.This was performed after the cleanup data has been submitted to the ICC-Ph and then subsequently uploaded in the TIDES database.

[35] Model basis and assumptions are as follows: The system for considered is the coastal mangrove area and the beach area as two separate compartments as shown from the Figure 3A assuming that plastics are well-mixed in the said compartments. The model has zero-dimension spatial resolution and is a pseudo-steady state model, where the plastic flows are assumed to be at steady-state such that the temporal dimension is removed. Additionally, the degradation of macroplastics into secondary microplastics is not accounted for in this model and the plastic litter transported in the riverine system is from terrestrial and tidal movement [32]

[36] The SPR model is built up on the basis of sources, pathways and receptors and can thus be used to assess any environmental pollution. It is also one of the specific applications of the MFA in environmental pollution studies. SPR modeling is characterized by its simplicity, its flexibility, and the ability to recognize relationships in complex systems. This makes it possible to consider the path of plastics through all areas of the aquatic, terrestrial, and atmospheric environment.

Hence, the said framework of digital transformation for marine plastics pollution which has been demonstrated in small scales (i.e., island [32] and barangay [33] levels) can serve as a basis for future research endeavors with the purpose of defining the extent of the plastics problem, specifically on its fate and transport to the environment; while recognizing that digital transformation for marine environmental protection is one of the priority research areas in the Philippine maritime sector.

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