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From Trash to Cash: How Block chain and Multi-Sensor-Driven Artificial Intelligence Can Transform Circular Economy of Plastic Waste?

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A B S T R A C T

Virgin polymers based on petrochemical feedstock are mainly preferred by most plastic goods manufacturers instead of recycled plastic feedstock. Major reason for this is the lack of reliable information about the quality suitability and availability of recycled plastics which is partly due to lack of proper segregation techniques. In this paper we present our ongoing efforts to segregate plastics based on its types and improve the reliability of information about recycled plastics using the first-of-its-kind block chain smart contracts powered by multi-sensor data-fusion algorithms using artificial intelligence. We have demonstrated how different data-fusion modes can be employed to retrieve various physico-chemical parameters of plastic waste for accurate segregation. We have discussed how these smart tools help in efficiently segregating commingled plastics and can be reliably used in the circular economy of plastic. Using these tools segregators recyclers and manufacturers can reliably share data plan the supply chain execute purchase orders and hence finally increase the use of recycled plastic feedstock.

A R T I C L E I N F O

Keywords:
plastic recycling; circular economy; plastic waste; waste segregation; blockchain; smart contracts; multi-sensor; data fusion; artificial intelligence; AI; sustainability; waste-to-value; landfills

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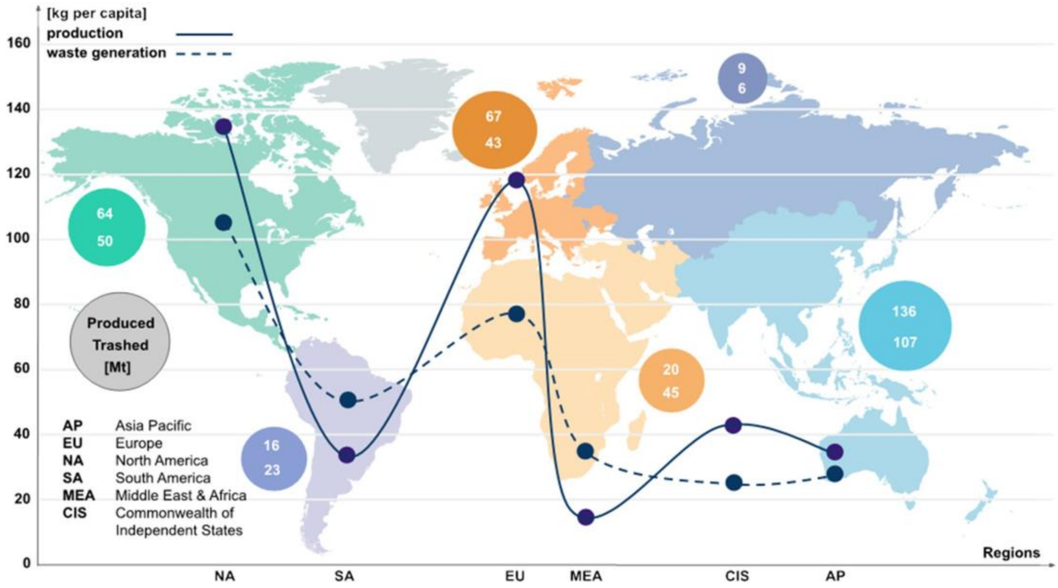
1. INTRODUCTION

Today plastic has become both a symbol of human ingenuity and absurdity. We created this remarkable material with different properties and capabilities. However we did not pay proper attention in managing this resource after its use (Thompson et al.2009). As a result in 30 years our oceans will contain more plastic by volume than fish (WEM2016). Illicit oil-spills from ships (Bhatt et al.2018;Sankaran and Fortuny-Guasch2004) and massive oil-refinery accidents (Dean et al. 1990) in oceans often catch our attention and several studies have been reported to mitigate and manage these marine pollutions (Brekke and Solberg2005 ;Fingas2016; Sankaran2019 b2020). However we do not take responsibility for our collective actions that are silently poisoning the entire marine ecosystem in a different way in the form of plastic pollution.

Worrying? Of course this is not a sudden change. The historical data in retrospect tells us the dramatic development of this silent chaos. 15 million tonne of plastic was globally produced in 1964 which grew to 311 Mt in 2014. This further grew to 359 Mt in 2018 (PlasticsEurope20152019; WEM2016). Present estimates warn us that this figure will triple in the next three to four decades (Lebreton and Andrady2019). Figure1illustrates annual virgin plastic production (figures on the top) and plastic trashed as waste (figures on the bottom) in million tonne across different regions in year 2010 (PlasticsEurope2011). Additionally the per capita virgin plastic production (solid line) and waste generation (dotted line) are also plotted giving different regional perspectives.

Figure 1. Annual virgin plastic produced (top) and trashed as waste (bottom) in million tonne for different shaded regions in year 2010. Per capita virgin plastic production (solid) and waste generated (dotted) for different shaded regions.



In the case of Asia-Pacific (AP) region the per capita plastic production and waste generation are low as seen in Figure1. This is because the population of this region is the highest in the world with China and India together contributing to more than one third of the world's population. It would be worth mentioning that in 2018 China alone contributed to about 23% of plastic production and 21% of waste generation in the world (PlasticsEurope2019;Ritchie and Roser2019).

Crazy as it may sound there is no simple way to wish away this pervasive material. At least there is a common understanding on how plastic is polluting our water bodies destroying wildlife entering our food-chain and ultimately damaging our well-being (Jambeck et al.2015;Rochman et al.2013) . Most of the countries around the world are committing resources to collect and recycle this material (Giacovelli2018;UNEP-AR2018;UNEP-SP2018). But this is far away from ideal scenario (Hook and Reed2018).

Away from eyes away from mind best reflects our attitude about plastic wastes because most of it is still ending up in landfills. In 2015 globally about 50–60% of the total plastic waste was discarded or dumped in landfills 20 30% was incinerated and about 10–20% was recycled (Geyer et al.2017; Ritchie and Roser2017). Considering only developing or underdeveloped countries the amount of plastic waste sent to landfills is much higher than the global average. Various reckless dumping activities have contributed to land and marine pollution which will take decades if not centuries to rehabilitate (Barnes et al.2009). The next viable option to dumping is to incinerate plastic waste to produce energy however this approach has two drawbacks. Firstly by burning the plastic waste we are potentially destroying valuable feedstock. Secondly by doing this we are going to only increase the influx of virgin feedstock mainly derived from fossil fuel-based sources into our ecosystem. Hence putting us on an ever increasing sisyphean task.

Moreover only by efficiently recycling plastic waste we can fight marine and land pollution. In 2016 Plastics Europe and the European Association of Plastics Recycling and Recovery Organisations (EPRO) commissioned a study across EU-28 countries plus Norway and Switzerland for monitoring plastics waste recycling and recovery (European Commission2018;Plastics Europe2017). This study reported that the collected annual post-consumer plastic waste reached 25.1 Mt. The recovery of feedstock through recycling reached 72.7%. This study further highlights that among all plastic waste the packaging plastic materials have the highest recycling and recovery rates for Europe 42% (PlasticsEurope2019). During this reporting period for the first time the amount of recycling for plastic waste was more than what went into landfills. These figures are consoling however they do not reveal the ground reality in many countries.

Producing plastic products is carbon-and energy-intensive. These processes emit huge amount of greenhouse gases either directly or indirectly. If we take into account the complete supply chain of the source of various plastics and their respective disposal pathways overall carbon footprint increases tremendously. Regardless of post-disposal pathways landfilling incinerating or recycling we have to deal with resulting carbon emissions. In 2015 global carbon emission due to virgin (fossil fuel-based) plastic production was approximately 1.8 Gt. To put this into perspective this amount corresponds to roughly 3.8% of the overall global carbon emission in that year due to various human activities. If we take into account all the emissions coming from the post-disposal and recycling processes the carbon footprint of plastics during their entire life cycle will be much higher (Chaffee and Yoros2007;Pilz et al.2010;Zheng and Suh2019).

In reality even in Europe only about 10 countries have less than 10% of their plastic waste going to landfill. Among the 28-Member-States European Union (EU) this figure is disturbingly more than 50% for nearly 11 countries (Gourmelon2015). Obviously increasing the amount of recycling in terms of material recovery will reduce the fossil fuel consumption and related greenhouse gas (GHG) emissions (Zheng and Suh2019). This will also spare us from not depleting valuable natural resources. But then why are we not taking this logical next step seriously? Are there structural challenges in the pathways to plastic recycling? If then what are recent technological developments that can help us in the battle against this human-induced absurdity?

We will address these points in this paper. In particular we will discuss some of the ongoing efforts in Radical Innovations Group in domain of circular economy of plastic waste. In addition to the ongoing activities in circular economy of plastic waste we also studied various other processes involving recycling of wastes and emissions (Patil and Sankaran2020ab;Sankaran 2019a). We have developed first-of-its-kind blockchain smart contracts powered by multi-sensor artificial intelligence (AI) tools that are highly useful for the circular economy of plastic. We will discuss how these smart tools help segregators recyclers and manufacturers to reliably share data plan the supply chain execute purchase orders to increase the use of recycled plastic feedstock. In the following we will first look at some of relevant recent developments and challenges in the circular economy of plastic.

2. PLASTIC CIRCULAR ECONOMY—RECENT DEVELOPMENTS AND CHALLENGES

There are different classifications of the plastics based on their constituent components reusability synthesis process etc. In this work on circular economy of plastic waste we classify them in three types namely recyclable non-recyclable and complex or unknown. The types of plastics considered here are as per the European classification described in (European Commission1997). The most commonly produced plastics under these types are shown in Figure2.

Figure 2. Different types of recyclable non-recyclable and complex plastics.

2.1. *Recent Developments*

We analysed annual plastic production data available for years between 2011 and 2018 as shown in Figure3. This data reveals that based on different types of plastics about 40–48% of annually produced plastics are non-recyclable. About 19–30% are potentially recyclable and nearly 20–27% fall under complex or unknown category (PlasticsEurope2011,2012,2013,2014,2015,2016,2017,2018,2019).

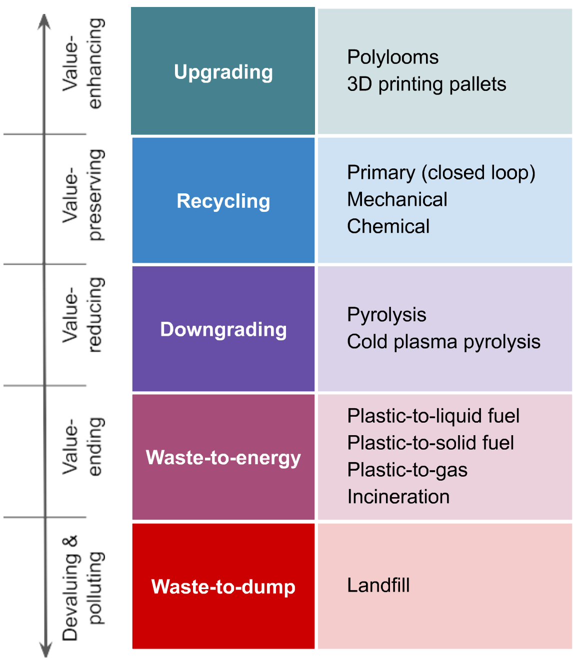
When we say potentially recyclable it only means there is a scope for recycling however whether we actually recycle them or not depends on how we handle them after their end-of-life. Likewise most of the non-recycling plastic has the potential to be converted in waste-to-energy. But disturbingly they are often dumped in oceans and landfills (Bläsing and Amelung 2018;Derraik 2002;Haward 2018;Jambeck et al 2015;Parker 2015;Wong et al.1974).

Cities and suburbs are main sources of plastic waste that ends up in landfills and water bodies. Various organised efforts in the form of waste collection are in place in many regions. For example in cities and suburbs with high density of population truck-based come $ collect schemes are becoming popular. Done on a weekly- or biweekly-basis in different neighbourhoods they become commercially feasible following the economies of scale. However in rural areas with less population density go & return schemes are economically-efficient (Hopewell et al.2009).

Figure 3. Potentially recyclable non-recyclable and complex plastics based on global annual production data for years between 2011 and 2018.

Different industrial processes to recycle various types of plastics are shown in Figure4. These pathways differ in their underlying technologies. Each of these processes have their advantages and disadvantages which need to be properly weighed before making a decision (Singh et al. 2017). Important industrial processes include pyrolysis (Adrados et al.2012;Kaminsky1992) plastic waste-to-energy (Kunwar et al.2016;Miskolczi et al.2004;Wong et al.2015) chemical and mechanical recycling (Ragaert et al.2017;Shen and Worrell2014). Though we term them plastic waste there is an inherent material value (cost per unit mass) to the original feedstock that is retrievable from the plastic waste. One can enhance preserve reduce end or dump this inherent material value depending on the steps we take to process them.

Figure 4. Different pathways to process plastic waste.



2.2. Challenges

Before addressing the main challenges we need to pay attention to key factors influencing plastic recycling. First the price of the recycled plastic feedstock compared to virgin feedstock is a primary factor on which most plastic manufacturers base their purchase decisions. If the price is lower or comparable to that of virgin polymers then the quantity and quality of the recycled plastic feedstock come into question. These three factors (price quality and quantity) are important drivers of the demand-side for recycled plastic polymers (Eriksen et al.2018).

In addition to the above factors the price of oil directly drives the price of virgin feedstock. In turn the price of virgin polymers set the upper limit for the selling price of recycled plastic feedstock. Though increasing oil prices directly pushes the price of virgin polymers high this increase makes recycled polymers more attractive (Ruhl2019). That being said there will be of course an indirect increase in the cost of plastic waste collection processing and distribution. This however will not be so dramatic as in the case of virgin polymers (Hopewell et al.2009).

The next big challenge is the notion of polymer quality. Generally manufacturers assume that the recycled polymers are poorer in quality compared to their virgin counterparts (Eriksen et al.2018). Though there is a level of truth in this exceptions are possible and needs to be supported by proper information.

Another fundamental challenge to overcome is the cost of recycling compared to alternative forms of plastic waste disposal. When reprocessing cost is very high compared to dumping or incineration and when the demand for recycled polymers is also low there is low motivation to circular economy of plastics. In many poor and developing countries where land cost is low and poorly regulated this is unfortunately the case (Dhokhikah and Trihadiningrum2012;Driessen 2003). Hence most of the potentially recyclable plastics end up being burnt or dumped in landfills. Recently many developing countries are seriously regulating their plastic waste policies and shutting down illegal recycling dumping or incinerating activities (Brooks et al.2018). We can overcome this challenge only when the demand for recycled plastic feedstock increase and cost of dumping becomes prohibitively high. Furthermore when waste-to-energy becomes less commercially attractive or highly regulated there is a positive drive for increased recycling.

Finally it all boils down to increasing the demand for recycled polymers. Though price is an important driver we cannot bring in big changes in this value-chain only by bringing the price of recycled plastics lower than that of their virgin counterparts. We need to also overcome a bigger challenge which is the lack of reliable information about their availability quantity quality and suitability for a specific application. Without such a reliable information it will be difficult to motivate manufacturers to procure more recycled feedstock.

We will briefly address how we are able to help manufacturers get reliable information about the availability quantity and quality of recycled feedstock using advanced block chain and AI technologies. Furthermore if we are able to calibre and derive grades for different recycled polymers we can assess the suitability of recycled polymers for various applications. This helps in transforming information to actionable intelligence and provides additional incentives to participate in the block chain platform.

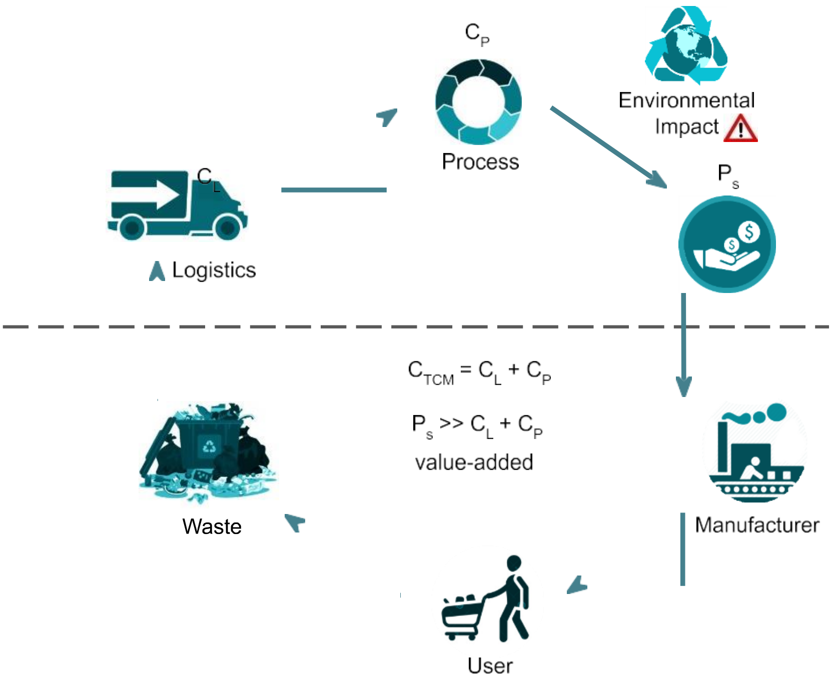
3. VALUE OF WASTE IN CIRCULAR ECONOMY

First step towards circular economy plastic is to understand the actual potential for creating value. For this we have followed a process that we term as total costing method (TCM). In TCM we account for cost incurred in each step of the circular economy starting from the waste collection point to the final destination. That is the (waste) material starts its journey towards the final destination which could be recycling plant incineration plant or landfill. There are two stages which incur costs namely logistics and processing. Depending on how much the process adds (or removes) value we have 5 types of processes namely upgrading closed-loop recycling downgrading waste-to-energy and dumping. The cost of the material is going to step-by-step increase from the point of waste collection to their respective destination. Even if they are just going to be dumped we have to take into account logistics and environmental costs. The latter is difficult to estimate as plastics take more than 400 years to degrade and most of it still exists in some form or the other after being dumped in land or ocean.

According to the statistics for years between 2000 and 2015 roughly 15 to 25 % plastic wastes are incinerated and 10 to 20 % are recycled (Ritchie and Roser2019). Hence most of it still ends up in landfills and the cost of rehabilitation is considerably high material (CTCM = CL + CP) after their respective processes as illustrated in Figure5. The selling price the sum of logistics (CL) and processing (CP) costs is the total transactional cost of the processed of the material (PS) should be more than the CTCM for any recycling process to be profitable. Here we have not taken into account the cost of environmental degradation. To incorporate environmental cost we need further investigation to carefully study the short- medium and long-term impacts of the respective processes.

In the next section advanced tools developed to help manufacturers get reliable information about the availability quantity and quality of recycled feedstock are briefly discussed.

Figure 5. Total carbon footprint for plastic waste recycling pathways



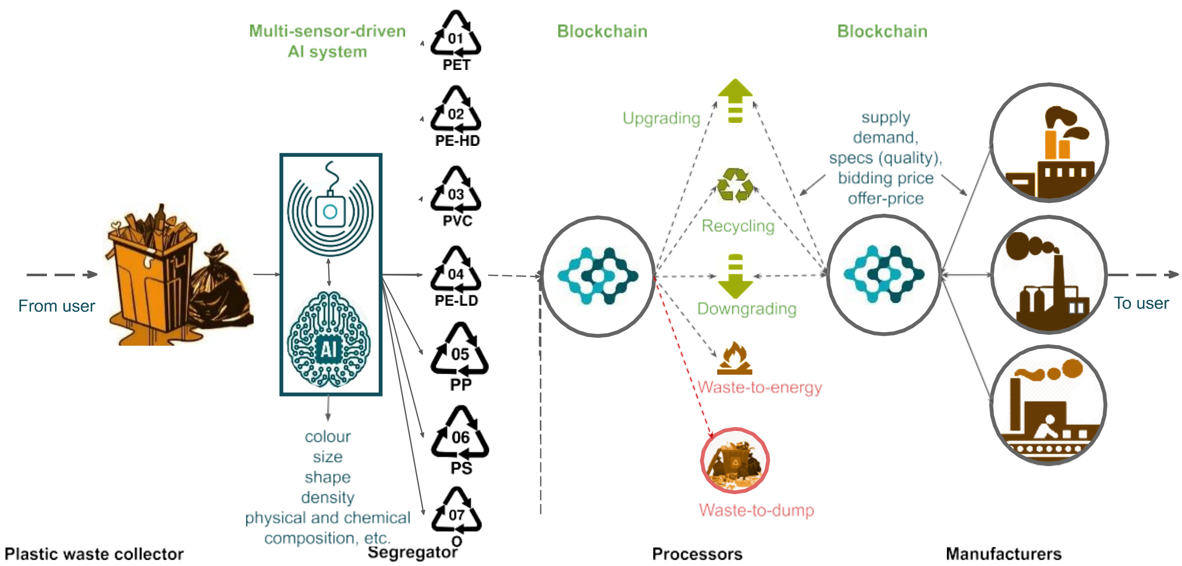
4. MULTI-SENSOR-DRIVEN AI AND BLOCKCHAIN TOOLS

We would like to highlight the ongoing work in tool developments using block chain and multi-sensor-driven AI system in Radical Innovations Group. We will shortly discuss multi-sensor-driven AI system before describing the block chain platform.

At the segregation stage as shown in Figure6 we employ different type of sensors supported by AI. Multi-sensor data fusion has been very successful in training intelligent robots for various tasks (Luo et al.1988;Masoumi et al.2012;Mitchell2007;Scott1995). Some researchers have tried combining multi-sensor data fusion with neural network to identify and segregate plastic waste (Scott and Waterland1995). The data about the shape colour and texture are retrieved from high-definition optical sensors (cameras). Using this for example we can separate certain shaped or coloured plastic bottles. We can also employ (near-infrared) laser diodes. The light absorption spectroscopy of plastics particularly in the wavelength-range from 300 to 3000 nanometre showed new possibility of optical sensing of plastics. Near-infrared laser diodes are also increasingly used to study the resonant frequencies of different plastics. These laser sensors can differentiate six types of detectable plastics namely PET (polyethylene terephthalate) PE (polyethylene) PVC (polyvinyl chloride) PP (polypropylene) PS (polystyrene) and ABS (acrylonitrile butadiene styrene). Essentially these sensors differentiate different grades of plastic based on the resonant frequency of each type of plastic. Those frequencies at which the absorption spectrum of the plastic has a peak they are called as resonant frequencies. Different plastic molecules have different resonant frequencies. By scanning the plastic wastes using these laser detectors over a range of frequencies we can find their resonant frequency. Depending on their resonant frequency we can identify the type of plastic. Recently researchers have tried using advanced terahertz technologies for plastic identification (Hailu and Saeedkia2017). These technologies can further help in accurate identification and segregation of plastic waste. For segregation based on colour manual separation is not a good option for industrial scale operations. Taking into account both the speed and accuracy required for industrial scale set-ups these technologies can yield nearly 99% accuracy for colour-based segregation and 95-98% accuracy for plastic type-based segregation (Inada et al.2001;Scott and Waterland1995;Zhu et al.2019).

The role of AI in this multi-sensor platform is to minimize uncertainties and enable efficient and intelligent segregation. For example AI can train the segregation system to recognize two bottles of same type even if one of them looked very different to the other (deformed or discoloured). In these instances the AI can train the system to properly recognise and separate them accurately. The efficiency of the present multi-sensor-driven AI implementation for segregating plastic wastes is tested in various practical scenarios. Discussions regarding the outcomes of these studies are outside the scope of this present paper and will be presented elsewhere.

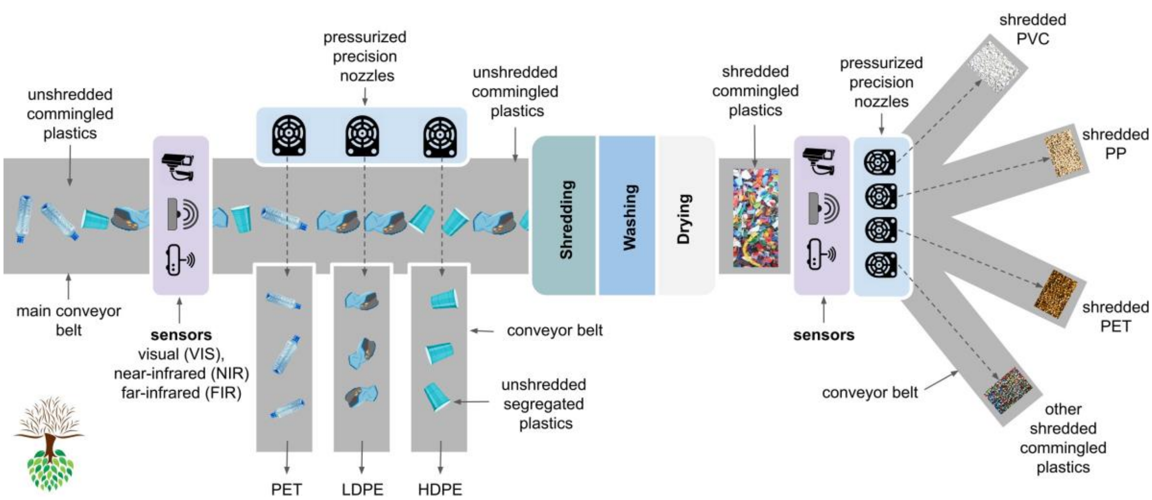
Figure 6. Blockchain and multi-sensor-powered artificial intelligence interfaces for plastic waste recycling.



4.1. Multi-Sensor-Based Plastic Waste Segregation

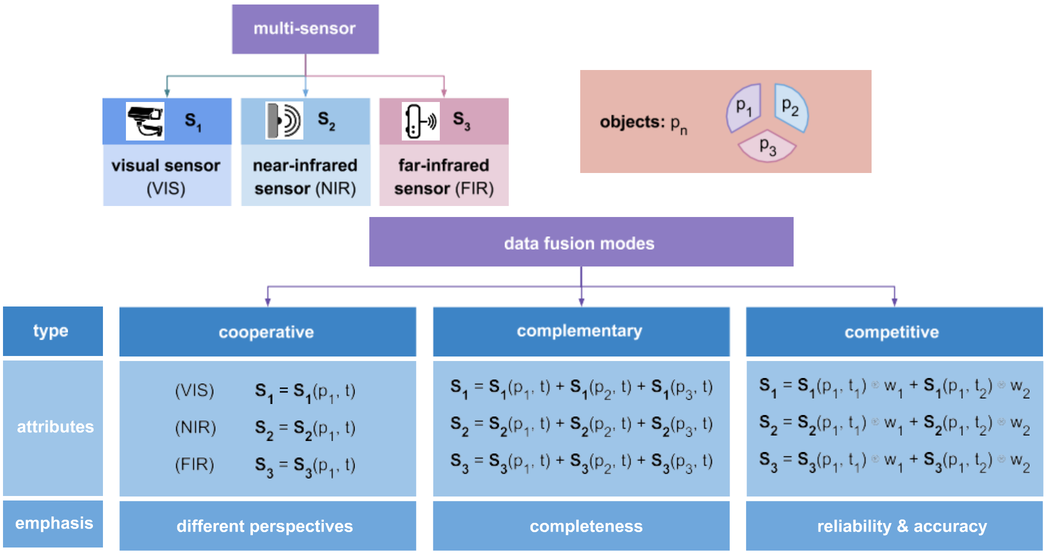
Segregating commingled plastic waste is a challenging task. The amount of plastic recycling directly depends on the efficiency and accuracy of separating plastics into their respective categories based on colour (pigments) chemical composition (plastic type) and source of plastic waste. We have developed a multi-sensor-based segregation process that uses three types of sensors. They are classified based on their operating frequencies as visual (VIS) near-infrared (NIR) and far-infrared (FIR) sensors. These sensors retrieve different types of information (attributes) such as colour physical and chemical compositions shapes etc. about the plastic waste. These attributes are used to segregate plastics into different types. One of segregation process flow models developed in Radical Innovations Group is illustrated in Figure7.

Figure 7. Segregation of commingled plastic waste into respective categories using multi-sensor data. © Radical Innovations Group.



We will briefly describe three data-fusion modes employing three types of sensors. They are called *cooperative complementary* and *competitive* data-fusion modes and are illustrated in Figure8. Consider an object with three different parts made of three types of plastics denoted as p_1 p_2 and p_3. And let the data retrieved from VIS NIR and FIR sensors are respectively given by S_1 S_2 and S_3. The cooperative mode is the most basic data-fusion mode where all three sensors VIS NIR and FIR are employed in parallel to get different information about the same object. In the case of VIS sensor data we will get the visual image of p_1 as in the case of an optical camera. From NIR and FIR sensors we can retrieve the absorption spectrum over arange wavelengths (typically in the range of 1–1000 μm). The complementary mode of data-fusion helps us to retrieve the overall assessment of the *complete* object using different sensor data. Lastly in the competitive data-fusion mode data samples of the same object taken at different time steps are proportionately mixed using different weights.

Figure 8. Multi-sensor cooperative complementary and competitive data-fusion modes.



4.2 Block chain Smart Contracts

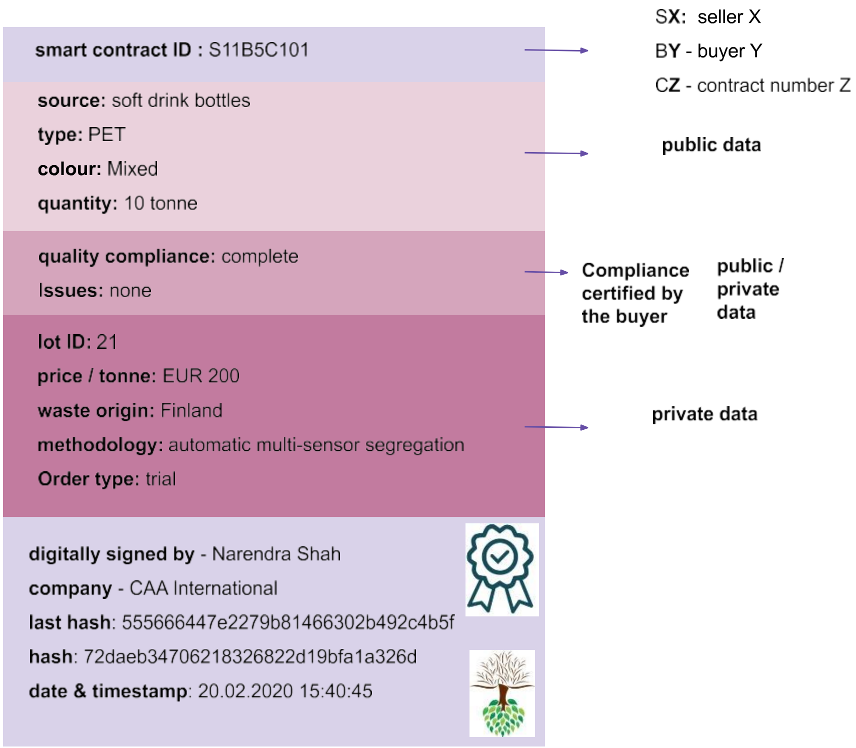
The block chain technology serves as a trust-based platform between plastic waste segregators recyclers and recycled feedstock buyers (manufacturers). The block chain network has distributed but not copied digital information (Adebiyi Abiola et al 2019;Crosby et al 2016;Drescher 2017;Kouhizadeh and Sarkis 2018;Kouhizadeh et al.2019;Mansfield Devine 2017;Romano and Schmid 2017;Sekhri 2018;Wang and Qu2019). This digital information is validated by various partners during each transaction. A transaction is an exchange of information between segregators recyclers and manufacturers. Information transacted contains data regarding supply demand specifications (quality) bidding- and offer-price as illustrated in Figure6. A few use-case examples employing multi-sensor-driven AI for plastic waste segregation and block chain platform for circular economy of plastic waste are currently under investigation in Radical Innovations Group.

In the original design of block chain one gets rewarded for participating in the validation process using digital currency. In our model for simplicity we have focused only on the backbone without the reward system to showcase the use of this technology for plastic circular economy. The security and transparency of the platform is derived from the fact that all the information is stored on a distributed block hain ledger. The access to information powered by block chain platform allows participants to exchange and validate information about supply demand specifications bidding and offer-prices. In sum, the participants in the block chain platform are rewarded by various actionable intelligence that allow for efficient planning of supply-chain operations and cashflow. This essentially will lead to animproved resource efficiency and a profitable model for the circular economy of plastic waste.

In the block chain system currently being developed in Radical Innovations Group for modelling plastic circular economy we have developed two types of smart contracts depending on the stage of raw materials being transacted. In the first type the smart contract is typically between a supplier of the segregated plastic waste (segregator) and a prospective buyer (example closed-loop recycler). The second type of smart contract is typically between supplier of recycled plastic feedstock and prospective plastic goods manufacturer. Consider an example smart contract between segregator and closed-loop recycler shown in Figure9. There are two types of data in this example smart contract namely public and private.

The public data is open for the validators to scrutinize and approve. The private data however is closed information only accessible to the seller and buyer involved in this contract. The validation of the private data is only possible through the buyer. Typically information related to price segregation methodology origin of waste materials order-type are contained in the private data. These information are hidden not to compromise the competitive-edge of each seller offering similar products. Most importantly the buyers can validate and approve information related to quality compliance and issues related to purchased products. This information related to quality compliance and issues can be kept public or private depending on preferences set in the smart contract. Additionally each smart contract will be digitally signed and time stamped through a validation protocol.

Figure 9. Example block chain smart contract between a plastic waste segregator and a closed-loop recycler. © Radical Innovations Group.



4.3 Remarks Related to Ongoing and Future Work

Our multi-sensor data-fusion algorithms and the block chain interface are currently tested for various practical scenarios. Efficiency of multi-sensor data-fusion algorithms implementations of different block chain validation protocols and the overall supply-chain impact parameters such as segregation efficiency accuracy block chain user-satisfaction data integrity transparency and validation etc. are currently being evaluated using those practical scenarios. Details of these assessments are outside the scope of current paper and will be presented elsewhere.

5. CONCLUSIONS

We addressed some of the structural challenges emerging due to the lack of improved technologies in plastic waste segregation and recycling processes and the lack of reliable data about recycled plastics. We have showcased how multi-sensor data fusion tools using artificial intelligence help in accurate segregation of commingled plastic waste based on the physico-chemical parameters such as colour polymer type density etc. Furthermore we have demonstrated using a trust-based block chain platform how information about the suitability quality compliance bid- and offer-price and availability of recycled plastic feedstock can be reliably shared between segregators recyclers and manufacturers. These block chain smart contracts powered by multi-sensor data-fusion will encourage manufacturers to confidently procure more recycled plastic feedstock and hence reduce our increasing dependence on fossil-fuels. As a work in progress we are currently testing these advanced tools with different early-stage adopters to gain more real-time insights and thereby increase impact of these tools in mainstream usage.

Conflicts of Interest:

The authors declare no conflict of interest.

Abbreviations

The following abbreviations are used in this manuscript:

CO2 carbon dioxide

GHG greenhouse gas

CCS carbon capture and storage CCU carbon capture and utilisation CAGR combined annual growth rate CH4 methane

CH3OH methanol

NH3 ammonia HCOOH formic acid

ROI return on investment

PPP public private partnership CAPEX capital expenditure

OPEX operational expenditure AIartificial intelligence

Gt giga tonne

Mt million tonne

EU European Union

EPRO European Association of Plastics Recycling and Recovery Organisations GHG greenhouse gas

TCM total costing method

CL cost of logistics

CP cost of processing

CE cost of environmental impact

CTCM total transactional cost of processed material

PS selling price of material

PET polyethylene terephthalate

PE polyethylene

PVC polyvinyl chloride

PP polypropylene

PS polystyrene

ABS acrylonitrile butadiene styrene nm nanometre

specs specifications

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