Exploring Plastic Waste Identification and Sorting Through NIR Spectroscopy and Automated Colour Sorting

By

Erin McInnis

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Dean of Science

Supervisor: Dr. Nola Etkin

Department of Chemistry

University of Prince Edward Island

Charlottetown, Prince Edward Island

This thesis is dedicated to my parents, who encouraged me to have faith in myself, and taught me the importance of resilience and perseverance.

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List of Abbreviations and Symbols

AI	artificial intelligence
APR	Association of Plastic Recyclers
ATR	attenuated total reflection
BPA	bisphenol A
BFR	brominated flame retardant
CCD	charge-coupled device
cm^{-1}	wavenumber
DA	discriminant analysis
ΔE	colour difference (delta E)
EPS	expanded polystyrene
FSDE	Faculty Sustainable Design Engineering
FTIR	Fourier transform infrared
GPGP	Great Pacific Garbage Patch
GHG	greenhouse gases
HD	high definition
HDPE	high-density polyethylene
IWMC	Island Waste Management Corporation

km^2	square kilometers
LED	light emitting diode
LDPE	low-density polyethylene
NIR	near infrared
nm	nanometer
PBT	poly(butylene terephthalate)
PCA	principal component analysis
PE	polyethylene
PEI	Prince Edward Island
PEN	poly(ethylene naphthalate)
PET	polyethylene terephthalate
PLA	poly(lactic acid)
PP	polypropylene
PPT	poly(propylene terephthalate)
PS	polystyrene
PVC	polyvinyl chloride
RIC	resin identification code
XRF	X-ray fluorescence

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Abstract

Plastic waste recycling has become a growing concern throughout the world. In Canada, three million tonnes of plastic waste are produced every year, but only 9 % of it is actually recycled. The remaining plastics are either incinerated, placed in landfills, or mismanaged and pollute the environment. In Prince Edward Island (PEI), plastic waste is sorted manually. If a plastic item can’t be identified, it can’t be recycled. Colourful plastics will also often go unrecycled due to manufacturers finding them undesirable.

In order to address these issues, automated sorting could be implemented instead. Two types of automation that see some use in the industry are near infrared (NIR) spectroscopy and colour sorting. In this thesis, the identification capabilities of NIR spectroscopy were tested on six common household plastics. A spectral library was created from the samples and the correlation percentages for the plastics was roughly 86 %. NIR could be used to correctly identify every plastic with the exception of high-density polyethylene (HDPE) and low-density polyethylene (LDPE), which both correlated to each other. Due to its presence in the recycling industry, NIR has some potential to be implemented.

A fully automated colour sorting apparatus was used to explore the effectiveness of colour sorting. Three different colour inputs could be examined at once. Black, white, red, and dark gray samples were tested, and black samples could be successfully separated from the other colours. Other colour combinations were unable to be tested, so automated colour sorting will need to be further studied.

Chapter 1: Introduction

Chapter 1.1: Background

When plastics were first invented, no scientist could have anticipated the impact they would have on the planet one hundred fifty-four years later. The first synthetic polymer, celluloid, was invented in 1869 by John Wesley Hyatt as an alternative to ivory.[1] Celluloid inspired the further developments of plastics, such as the invention of Bakelite™. The world saw a boom in plastic production during World War II due to versality of Nylon used for military supplies. The mass production of plastics continued after World War II ended.

This boom in production has continued into the 21st century. From 2000-2019, plastic production and waste generation doubled to reach 460 million tonnes and 353 million tonnes respectively on a global scale.[2] However, only 9 % of this plastic waste is actually recycled. The remaining plastic waste is either incinerated, placed in landfills, or mismanaged. Canada follows a similar trend with its recycling methods. 3 million tonnes of plastic waste are produced every year in Canada, but only 9 % of it is recycled.[3]

Plastic mismanagement and pollution have become particularly concerning issues. Plastic waste first began to be sighted polluting the ocean in the 1960s.[1] Carpenter et al. published the first scientific article detailing their observations of polystyrene (PS) spherules in the waters of the New England region.[4] The amount of plastic pollution in the oceans has spiraled out of control throughout the years and resulted in the infamous Great Pacific Garbage Patch (GPGP). The GPGP covers 1.6 million km^2 between Hawaii and California.[5] Celluloid was praised for being a substitute for ivory, which would reduce the need to slaughter elephants.[1] However, one hundred fifty-four years later, plastic pollution now causes roughly 100,000 deaths in marine animals every year.[6]

Chapter 1.2: Current State of Plastic Recycling

When plastics first started to be seen as a problem, recycling practices were introduced by the plastic industry.[1] Today, plastic recycling is a multistep process. The British Plastic Federation describes the mechanical recycling process in six steps.[7] For the first step, plastic items are collected and brought to a recycling facility. The next three steps of the process involve sorting, shredding, and washing the plastics. In the last two steps, the plastic shreds are melted and extruded into small pellets which can be re-used to form new products. This process is not without its flaws. The main issue that will be addressed in this thesis is the fact that some plastics never make it through the sorting step.

Plastics must be sorted for a variety of reasons. For example, magnets are often used to remove metallic materials that could have been mixed into the collected blue bags.[8] Even after removing all non-plastic materials, the plastics are further sorted in order to separate them by their type. The different types of plastics will be further discussed in Chapter 1.3. When the melting stage is completed, the plastic pellets will be reused. Plastics need to be sorted in order to remove different resins so that the new resin pellet obtained from the recycling process will be pure.[9] However, some of the sorted plastics will not be recycled. Light or thin items such as plastic films or bags are not often recycled.[10] Additionally, coloured plastics are not recycled because manufacturers don’t find them desirable for their products.[11] This causes plastic to go unrecycled and end up in landfills.

The sorting process can be done in multiple ways. Some sorting is done manually by employees who are trained to identify the different plastics. The Island Waste Management Corporation (IWMC) was toured and interviewed by Camren Chamberlain, a previous member of the Etkin research group, as part of an Advanced Research Project on PS.[12] His findings from the interview included that the plastic recycling in Prince Edward Island (PEI) is conducted by hand. Due to this, any items that have no symbols cannot be identified and are not recycled. Additionally, the plastic that does get recycled is shipped out of province. This means that PEI currently doesn't perform all of the recycling steps and instead relies on out-of-province companies to do so. The province then has to account for the price and greenhouse gas (GHG) emissions required to transport these plastics.

Another way that plastics could be sorted is by automation, which includes various spectroscopy techniques. Some of the common techniques used are Raman spectroscopy, X-ray fluorescence (XRF), and near infrared (NIR) spectroscopy.[13] Automation methods also include non-spectroscopic techniques. The many automation techniques will be further explored in Chapter 1.6.

Chapter 1.3: Plastics and Resin Identification Codes

As previously discussed, plastic sorting can be performed by hand. Employees can identify the composition of the various plastic items by using the resin identification code (RIC). The RIC is a label located on the bottom or sides of most plastic products. Plastics are labelled with a number from 1-7, and that number is surrounded by three arrows that form are triangle around the number.[14] The different numbers and the plastic they represent are further discussed in the remainder of Chapter 1.3.

1.3.1: Polyethylene terephthalate

The RIC #1 represents the plastic polyethylene terephthalate (PET or PETE).[14] The structure of PET is showcased in Figure 1. PET is a rigid and chemically resistant polymer, which gives it a high strength.[15] PET is typically used for creating clear bottles for various beverages.[14] This plastic is one of the more desirable plastics for recycling.

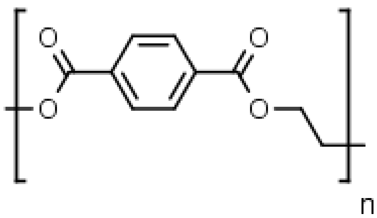

Figure 1: Structure of PET

The PET pellets obtained from extrusion have mainly been used to create polyester fibers, however, directly recycling the PET bottles has started to become a more popular method. This process is referred to as "bottle-to-bottle" recycling.[16] This means that PET bottles can be recycled and formed into new bottles. In order to perform bottle-to-bottle recycling, a process called "super-clean" recycling is required. This process involves three treatments on the PET flakes or pellets: high temperature, vacuum or inert gas, and a surface treatment.

1.3.2: High and Low-Density polyethylene

The polyethylene (PE) plastic comes in two variations. The different forms of PE are indicated by their density. High-density polyethylene (HDPE) is represented by RIC #2 and low-density polyethylene (LDPE) is presented by RIC #4.[14] The difference between the two PE plastics is that HDPE tends to be more linear, and LDPE has a more branched structure.[17] Additionally, LDPE is used to create transparent products whereas HDPE tends to create more opaque products. The density of HDPE makes it stiffer and more durable compared to LDPE.[18] This makes it ideal for various types of bottles such as shampoo or detergent bottles.[14] LDPE is a soft and pliable material, which makes it a common material for bags or tubs.[14,19] The structures in Figure 2 depicts the two variations of PE plastic.

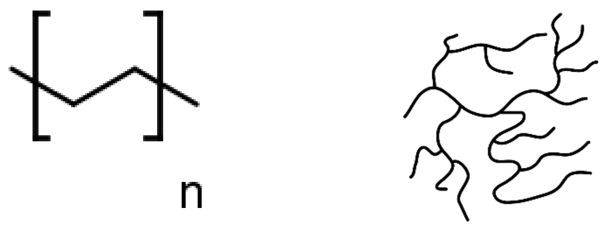

Figure 2: Structure of HDPE (left) and a possible structure of a LDPE plastic (right)[20].

Since these two plastics are derived from ethylene, they're recycled in a similar fashion. HDPE and LDPE that have been properly sorted can be shredded into flakes, which are then decontaminated and melted into pellets.[21, 22] Therefore, these two plastics can be recycled through the mechanical recycling method. PE in general has become a high-demand plastic, so recycling methods have been adapted to support these demands.[21] HDPE in particular can be recycled up to ten times depending on the quality of the item. This allows the life span of the HDPE to be increased and reduces the amount of HDPE that goes unrecycled. LDPE can be recycled to produce trash bags and envelopes, while HDPE can be recycled to form new products such as bottles, pens, or toys.[22, 23]

1.3.3: Polyvinyl chloride

The RIC #3 is used to represent the polyvinyl chloride (PVC) plastic.[14] PVC is often used for making building materials such as hoses, pipes, flooring, or cables. [14, 24] The aforementioned items such as household pipes aren't labelled with a RIC. The IWMC states that it accepts PVC on the latest version of their sorting guide infographic, but the findings from Chamberlain's interview indicated that most PVC goes unrecycled.[12, 25] The structure of PVC is shown below in Figure 3.

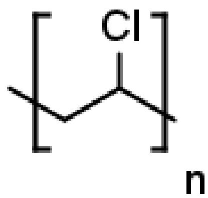

Figure 3: Structure of PVC

Many recycling facilities don't accept PVC. The facilities that do accept it, such as IWMC, may not actually recycle it.[12, 25] PVC can be recycled through mechanical recycling, the process described in Chapter 1.2, or through feedstock recycling.[26] Mechanical recycling is the preferred option throughout the recycling industry. However, additional steps are required in order to ensure a consistent quality in the materials.

Feedstock recycling, which can also be referred to as chemical recycling, is performed in a different fashion compared to mechanical recycling.[27] Feedstock recycling is performed in order to obtain the raw materials that were used in the original synthesis of the PVC product.[26] Thermal decomposition must be performed on the PVC in order to yield these raw materials or other chemicals, which can be used in a variety of ways in the chemistry industry.

However, there are also additional risks associated with handling chloride-containing materials. The temperature must remain stable during the thermal treatment to prevent dioxin from being produced, which is hazardous to human health.[26] The chlorine from PVC is also an environmental hazard, so the recycling process needs to be conducted in a precise manner. Both mechanical and feedstock recycling of PVC are expensive procedures, which could be deterring recycling facilities from utilizing these methods. Due to PVC not being accepted at many recycling facilities, it is one of the least recycled plastics.[28]

1.3.4: Polypropylene

The RIC #5 is used to represent the plastic called polypropylene (PP).[14] PP is a tough, elastic, and chemically resistant material that is often used for making plastic straws or microwavable food containers.[14, 29]. The structure of PP is shown below in Figure 4.

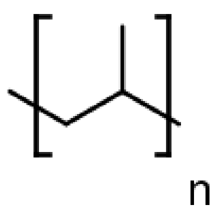

Figure 4: Structure of PP

PP is usually recycled through mechanical recycling.[30] Compared to other plastics such as HPDE and PET, PP is not recycled as much. For example, food containers made from PP aren't currently recycled because of the many guidelines for food-contact products.

1.3.5: Polystyrene

The plastic PS is represented by RIC #6.[14] The structure of this plastic is shown below in Figure 5. PS can be divided into two classes; PS and expanded PS (EPS).[14] The standard PS is brittle, whereas the expanded PS is a light, foamy plastic. This allows PS to be used for a variety of items such as yogurt cups, plastic utensils, or Styrofoam®.

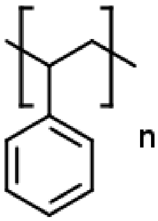

Figure 5: Structure of PS

The IWMC's 2020 version of their sorting guide infographic states that PS is not accepted with blue bag recycling.[31] It's common for other recycling facilities to deny PS as well.[14] Mechanical recycling of PS is a costly procedure, which has pushed recycling facilities away from using it.[32] There's also the additional challenge of recycling EPS because it is so lightweight, which makes it difficult to recycle.[33] EPS is bulkier than standard PS, which makes it difficult and expensive to ship away to be properly recycled.[34] This is why most facilities like the IWMC do not accept PS because even if they accepted PS, they would have to pay to transport the PS.

Due to the difficulties associated with PS recycling, research is being conducted in order to determine a way to increase the total amount of PS and EPS recycled. EPS is composed of roughly 95 % air and 5 % polymer, so effective recycling methods have been difficult to find.[35] A solvent was discovered to be capable of dissolving EPS by International Foam Solutions Inc.[36] Hardjono et al. were able to extract essential oil from orange peels which contain a molecule called D-limonene.[35] They tested several volume ratios and found that a ratio of 1:1:2 (essential oil: ethanol: water) was the solution that could dissolve the EPS the fastest.

Chapter 1.4: Other Plastics

The last RIC, #7, isn't used for one specific type of plastic. Instead, RIC #7 is a general label for all other plastics, which is why RIC label sometimes contains the word "other" in it.[37] #7 plastics can be pure or composed of multiple types of plastics. Some of these #7 plastics include nylon, polycarbonate, and polyesters. These plastics currently aren't accepted by the IWMC and other recycling facilities.[12] The problem with RIC #7 plastics is that the label doesn't actually indicate what the item is made from. Therefore, manual sorting can't be done with these plastics because an employee would have no way to identify the material. Alternative sorting methods could be used to address this problem. These alternative sorting techniques are further explained in Chapter 1.5.

Chapter 1.4.1: Polycarbonate

Polycarbonate can also be referred to as poly(bisphenol A carbonate). It is commonly used for items such as water bottles, electronics, or construction panels.[38] The structure of polycarbonate can be seen below in Figure 6. As its alternative name would suggest, polycarbonate contains bisphenol A (BPA). This chemical can enter the human body through food and drink containers or bottles.[39] This has caused some countries to ban the use of polycarbonate for baby bottles and other baby products.[38] Polycarbonate isn't recycled and is incinerated or placed in landfills instead. This accumulation of polycarbonate in landfills causes BPA to leach and pollute the environment.

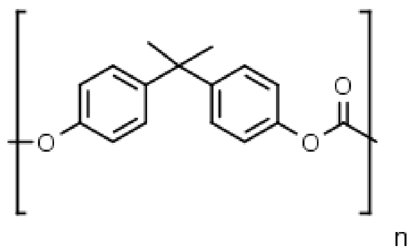

Figure 6: Structure of polycarbonate

Polycarbonate currently isn't accepted at most recycling facilities, however there is research being done in order to improve the handling of polycarbonate. Chemical recycling has become a promising option for polycarbonate recycling.[38] A variety of catalysts can be used to separate the BPA and carbonate. For example, methanol can be used in an alcoholysis reaction in order to depolymerize polycarbonate. This reaction will yield BPA and dimethyl carbonate. Other types of reactions that have been explored for the usage in chemically recycling polycarbonate include pyrolysis, hydrolysis, and aminolysis.

Chapter 1.4.2: Polyester

One of the #7 plastics is the group of polymers called polyesters. The general structure of a polyester can be seen in Figure 7. Based on this structure, PET can technically be considered as a polyester. PET is classified as RIC #1 and was already discussed. There are other types of polyesters that are classified as RIC #7 such as poly(ethylene naphthalate) (PEN), poly(butylene terephthalate) (PBT), poly(propylene terephthalate) (PPT), and poly(lactic acid) (PLA).[40]

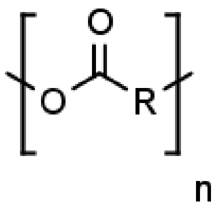

Figure 7: General structure of a polyester

These different subtypes allow for polyester to be used for a variety of products. For example, PPT can be used for making carpets and PBT can be used for stretched fabrics.[40] These polyesters have other applications besides fibers. For example, PBT plastic can be used for various machine parts like gears or bearings.[41] These polyesters would be considered RIC #7 and would therefore not be accepted in general recycling collections.

The recycling process of PLA has become a recent area of interest. PLA is actually a biodegradable plastic; however, the plastic can take over a year to fully degrade depending on the environmental conditions.[42] This can be problematic, especially if the PLA was polluting the ocean. Chemical recycling is a promising option for PLA recycling. If PLA undergoes a hydrolysis reaction, lactic acid will be yielded. From there, further reactions can be performed in order to obtain certain products. For example, a reduction reaction can cause the lactic acid to yield propylene glycol.

Chapter 1.4.3: Nylon

Nylon, also known as a polyamide, is one of the many plastics that make up RIC #7. Nylon can be used for textiles, films, and fishing line.[43] The structure of nylon 6,6 can be seen below in Figure 8. Nylon 6,6 is just one of the many types of nylon, but it is one of the most popular for manufacturing purposes.[44] As mentioned in Chapter 1.1, nylon had a historical impact on the way plastics are used due to its usage in military supplies in World War II.[1]

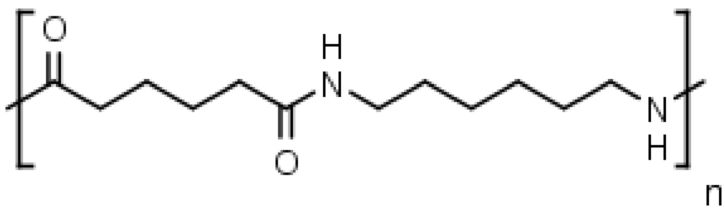

Figure 8: Structure of Nylon 6,6

The challenge with nylon recycling is that it is a difficult and expensive process.[45] Purity is an important consideration when recycling plastic products. Therefore, the recycled resin needs to be free from contamination. Nylon melts at a much lower temperature compared to other recyclable materials, which means some contaminants such as bacteria can remain. This is why the washing process is important for nylon recycling. However, this emphasis of the washing process contributes to the high cost of nylon recycling. Nylon is typically recycled through mechanical recycling. This process isn't performed in PEI since #7 plastics aren't accepted.[12]

Chapter 1.5: Plasticizers

Just like the #7 plastics, the RIC #1-6 plastics are not guaranteed to be made of one pure resin. For example, an item with a RIC #3 label might be composed of other materials besides PVC. These other materials are called plasticizers.[46] A plasticizer is a liquid or solid substance added to the polymer in order to give it different properties. There are four types of plasticizers: phthalates, decarbonates, phosphates, and fatty acid esters. Phthalates or fatty acid esters are often used with PVC. PVC is normally very strong and rigid, but a plasticizer can make it much more flexible. This allows for items such as shower curtains to be made from PVC. Therefore, plasticizers can allow polymers like PVC to become a much more diverse material. However, plasticizers can be troublesome for plastic separation and recycling because the products aren't pure. This can cause plastic identification to be more challenging.

Chapter 1.6: Automatic Techniques for Plastic Sorting

Manual plastic sorting is the current standard practice that the IWMC uses in PEI.[12] There are alternative methods that can be used to identify and/or sort plastics. Some of these methods are currently used in recycling facilities throughout the world, while other methods are being researched in order to determine their effectiveness and how they could possibly be implemented. The current alternative to manual sorting is automated recycling.[47] As mentioned in Chapter 1.2, some of these automatic methods include spectroscopic techniques like NIR and XRF. Other methods include shape recognition, optical sorters, and robotics.

Automatic sorting is a promising option for plastic recycling. In the United States, roughly 43 % of recycling facilities use a combination of manual and automatic sorting techniques.[47] 28 % of facilities rely solely on manual sorting and 29 % rely solely on automatic sorting. The downside of only using manual sorting techniques is that facilities report a lower throughput of materials through their systems compared to facilities that use automation. The different automation techniques and their effectiveness will be further discussed.

Chapter 1.6.1: Spectroscopic Techniques

A variety of spectroscopic techniques can be used for plastic sorting and identification. One of the spectroscopic techniques that can be used is NIR spectroscopy. This technology currently sees usage in some facilities throughout the recycling industry due to its growing popularity.[47] NIR sensors have been a topic of interest for some research groups that are testing the identification abilities. Zheng et al. examined NIR sorting of plastic waste through discrimination models.[48] They used a Fischer discriminant analysis (DA) model. DA models can be applied in a variety of fields, with the purpose of sorting different observations into groups in order to classify them.[49] In the case of plastic sorting, DA models can help researchers match the RIC to the spectral data obtained in their experiment. The experiment by Zheng et al. was able to detect PE and RIC #1, 3, 5, and 6 plastics and could identify an unknown plastic with 100 % accuracy using their DA model.[48]

Another NIR spectroscopy study by Wu et al. tested the classification capabilities of the technique with various discrimination methods.[13] They tested PP, PS, and several #7 plastics and found that PP was the easiest to identify because it was the only polyolefin among the plastics. They observed that the other plastics used in their experiment were more difficult to differentiate. The specifics of NIR spectroscopy and its functioning in plastic sorting will be further discussed in further detail in Chapter 2.

XRF is another spectroscopic method that can be applied to the plastic sorting process. X-rays will penetrate and be absorbed into the plastics, which will then emit fluorescent X-rays.[47] The fluorescence can then be used to determine which elements are in the compound. XRF particularly excels in identifying heavy elements, which makes XRF a potential option for sorting PVC. This also means that XRF has some applications in sorting other halogenated plastics. Some plastic products have brominated flame retardants (BFRs) added to them to make them less flammable.[50] However, these additives are toxic, and their usage has been limited in the European Union. Bonifazi et al. experimented with numerous BFR plastic waste samples and XRF. The XRF could determine the bromine content in each of the samples. The researchers then used principal component analysis (PCA). PCA is a tool that can be used to reduce the size of a data set by converting the variables into a smaller group.[51] PCA and DA were combined in order to sort their samples into two groups based on bromine content.[50] The group found this experiment to be successful and they believe their model could be expanded upon to include EPS. Currently, XRF is only used in the recycling industry to separate PVC from PET.[47]

Chapter 1.6.2: Previous Work by the Etkin Research Group

The Etkin research group has worked with different spectroscopy techniques in order to determine how PEI can implement new sorting technology. Julie VanLeeuwen researched the potential of Fourier transform infrared (FTIR) and Raman spectroscopy for plastic identification.[52] Numerous samples of common household RIC #1-6 plastics were analyzed with both techniques. FTIR isn't currently used at a large scale in the recycling industry, instead, most work with FTIR is performed in laboratory settings.[53] Raman spectroscopy is also rarely used for plastic waste sorting research, which was determined by Neo et al. when they reviewed different spectroscopy techniques used in recycling research.[54] The goal of VanLeeuwen's research was to create a method to identify and sort each of the RIC #1-6 plastics for each of the two spectroscopy techniques.[52] The findings from this study suggested that FTIR was negatively impacted by the labelling on the samples. Additionally, the colour of the sample impacted the fluorescence and would therefore impact the Raman spectra. FTIR could identify the samples at a smaller spectral region compared to the Raman samples. Raman spectroscopy, however, was able to identify the resin of some samples despite their labelling.

Chamberlain, another past member of the Etkin research group, researched methods to identify and characterize PS.[12] PEI does not recycle PS, so this project examined how the province could possibly begin to sort and identify PS. FTIR was used to confirm the resin concentration of samples with visible RIC labels. This methodology was based on the work done by VanLeeuwen. The 1300-1550 cm^{-1} region of the FTIR spectrum could be used to compare the sample of interest to a reference sample. The method was effective at identifying EPS foams and could also confirm the resin of samples with no visible RIC.

The work performed by the different Etkin research group members is all part of an overall project. The collective goal of this group is to test various automatic sorting systems on small scales in order to determine what type of system could be implemented in PEI. As mentioned in Chapter 1.2, PEI currently relies on manual sorting of plastics. The research done by the Etkin group can hopefully be used to implement a new system of sorting plastics. By doing this, the local recycling market could be strengthened in PEI. If more recycling is done within the province, it would also reduce cost and GHG emissions from transporting plastics to out-of-province recycling facilities. The objectives of this thesis and how it contributes to the overall project will be further explained in Chapter 1.7.

Chapter 1.6.3: Non-spectroscopic Automated Sorting Methods

There are other methods of sorting plastics that aren't based on spectroscopy. One of those techniques is the use of air classifiers.[47] An air classifier is designed to separate materials by having materials in a feed enter a column of air.[55] The air column will separate the materials based on their density or size. An example of how this application works is that impurities can be removed from plastic samples.[56] The labels on PET bottles are made from a different plastic, so an air classifier can remove those labels so they can be collected separately. A study by Feil et al. found that air classifiers could be used to sort PET, HDPE, and PP from municipal solid waste.[57] These three plastics were separated from the other plastics in the waste stream because they were heavy. When combined with NIR sensors, the researchers were able to identify these plastic samples as PET, HDPE, and PP.

A majority of the non-spectroscopic automation techniques sort plastics based on other factors besides their resin type. Eddy current sorting, for example, can sort materials based on whether or not they have ferrous properties.[58] An eddy current uses a rotor with an alternating polarity, which will repel non-ferrous metals. These separators can be used to remove metals from PET bottle recycling streams. Other machines and technology used for automated sorting include trommel screens, disc screens, and traveling chain curtains.[47]

Chapter 1.6.4: Artificial Intelligence-Based Sorting

Optical sorters can be used to separate plastics based on their type, colour, or shape.[47] These optical sensors would include the various spectroscopy techniques that were previously described. Another form of technology that can be used to sort plastics by these conditions is artificial intelligence (AI) sorters. In terms of the plastics industry, AI can be used to build sorting robots that automatically sort different plastics. A study by Wilts et al. tested a robot's ability to sort municipal waste through its AI.[59] The overall goal when it comes to AI-based sorting is to implement it into the recycling process in order to improve efficiency and the quality of raw materials obtained from waste. In order for the robot to sort plastics, it needed to be trained to recognize them. Wilts et al. used a series of steps to teach their robot to sort different waste materials. Samples were gathered and listed as a new fraction in the Intelligence Unit. The feed samples were then placed on a sorting belt so that the robot could scan and analyze them. The robot was equipped with a gripper, which allowed it to pick up objects that matched its data. The rejected objects were placed on the sorting belt again, and the robot scanned them. This allowed the AI to learn what types of samples it could match with its stored data and which ones it could reject.

Wilts et al. found that the robot could detect and sort a variety of materials.[59] Their experiment involved the use of HDPE boxes, films, cans, and other waste items. The purity and recovery of the samples obtained during the robot's performance were also calculated. The purity refers to how much material the robot could sort from a mixture of samples and the recovery reflected the amount of the material collected in comparison to the total amount of fed target material. The robot was able to recognize over 95 % of the samples presented to it. The average purity was 97 % and the average recovery was 67 %. This contrast was due to several problems such as the flow rate, the shapes of objects making them difficult for the robot to grab and the jamming of materials in the conveyor. Wilts et al. believe that, with further optimizations, robotic sorting could become a successful option for waste treatment.

The literature review by Lubongo et al. found that there are currently seven manufacturing companies in the United States that provide AI-based sorters.[47] AMP Robotics' AMP Cortex™ was one of the devices listed, which has a 99 % sorting accuracy.[60] Their equipment is used by RDS Virginia to sort PET, HDPE, and other materials. Waste Robotics Inc. is another manufacturing company, which is located in Quebec. According to their website, their complete robotic sorting systems have a minimum price of $ 185,000 (USD).[61] Their products can be customized to suit the consumer's needs, so RICs #1-6 can be sorted. Waste Robotics Inc. also states that their robots are long-lasting and usually require maintenance every three months. AI-based sorting might be difficult to implement in PEI due to the price of installing this equipment. Nevertheless, AI is an important area to discuss as the technology continues to expand.

Chapter 1.7: Research Objectives

As mentioned, this honours thesis project is part of the Etkin research group's project to improve the recycling process in PEI. In 2022, FTIR and Raman spectroscopy was used to test different plastic resins on a small scale.[52] In order to make a conclusion on what spectroscopic method would be most suitable, NIR will also need to be tested. VanLeeuwen was not able to test NIR due to there being no accessible technology. For this project, a NIR analyzer was provided by Direct NutriSciences which allowed for small-scale sample analysis. There are two objectives at this stage in the project. The first objective is to collect various resin samples in order to build a NIR spectral library. This library can then be used to identify the resin type of samples that aren't stored in the library. The results from this experiment can then be compared to those obtained from VanLeeuwen's FTIR and Raman experiment. Additionally, the advantages and disadvantages of each method will be compared in order to determine which one could potentially be implemented in PEI.

The second objective of this project is to explore other sorting methods that aren't based on plastic type. Density sorting was explored by VanLeeuwen through the use of a sink/float tank.[52] This project will explore colour-sorting through the use of a conveyor belt and colour sensor. A variety of coloured samples will be tested, and different colour combinations will be tested in order to determine how the sensor can differentiate between the coloured items. For both of the objectives, household RIC #1-6 plastics will be used.

Chapter 2: Near Infrared Spectroscopy

Chapter 2.1: Introduction to NIR Spectroscopy

NIR spectroscopy focuses on the absorption of energy corresponding to the vibration of atoms.[62] The technique measures the absorption in the 800-2500 nm (or 12500-4000 cm^{-1}) region.[63] This wavelength range lies in between the visible spectrum of light and the mid IR region. Therefore, the vibrations observed under NIR consist of overtones from the IR region.[64] This means that, depending on the specific spectral range on the NIR instrument, the spectrum would contain peaks that represent C-H, O-H, or N-H bonds. In the case of plastic resins, the C-H bonds would be the most prominent feature on the spectra. Figure 9 contains several spectra and highlights the peaks of absorbance for the different bonds.

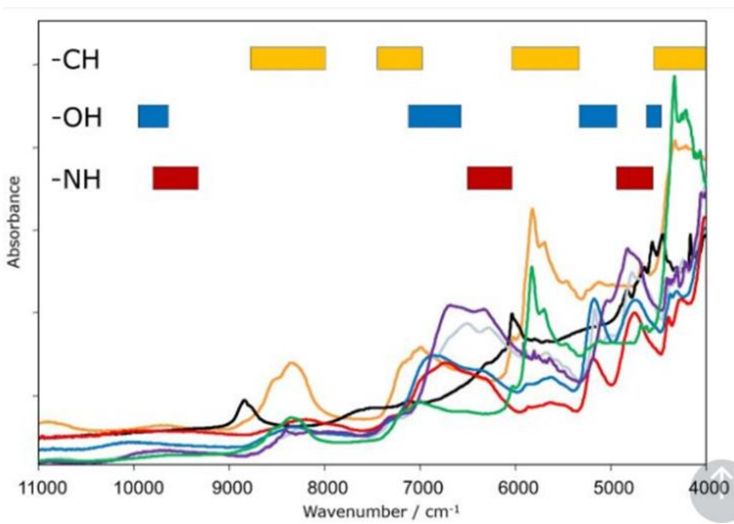

Figure 9: NIR absorption wavelengths of various structures.[64]

The peaks in Figure 9 showcase the overtones of the different bonds. For example, C-H bonds are typically observed around 3000 cm^{-1} in FTIR.[65] In Figure 9, the C-H peaks are absorbed around 6000 cm^{-1}, which are roughly twice the size of the 3000 cm^{-1} peaks. This means that peaks seen at 6000 cm^{-1} are the overtones of the C-H vibrations observed in FTIR.

In comparison to other spectroscopy techniques like FTIR, samples for NIR analysis are significantly easier to prepare.[66] This allows for three different forms of sample measurement: reflection, transflection, and transmission. Reflection is typically used for powders and other solids, whilst transflection is used for liquids and semi-solids. Transmission can also be used for clear liquids and solid samples such as grains.[64, 66]

Each of the measurement methods obtain a spectrum in different ways. In reflection measurement, the light source is located below the sample, and it reflects off the sample onto a detector.[64] The light source moves directly through the sample in transmission measurement and hits the detector. Transflection differs from reflection because the light source passes through the sample, hits a mirror, passes through the sample once again, and then reflects onto the detector. This versatility allows for a wide variety of samples to be analyzed with NIR spectroscopy.

NIR is often used alongside a spectral library. A spectral library is a collection of spectra used to identify and map different materials.[67] Therefore, a spectral library can be used to identify an unknown sample by comparing its spectrum to the spectra stored in the library. NIR spectral libraries have often been used to study soil samples. Viscarra Russel et al. created a NIR spectral library for soil sampling based on data they had gathered by reviewing studies throughout the globe.[68] A more recent study by Zhao et al. utilized NIR spectral libraries in order to predict the concentration of clay in Australian soil in order to determine the soil's quality for agricultural purposes.[69] Other applications of NIR include quality control and assurance in cosmetics, pulp and paper, chemical production, and other industries.[70] NIR spectroscopy can also be used for medical applications as a means to analyze tissues and diagnose diseases.[71] NIR spectroscopy has applications in the recycling industry, which is why the technique was one of the key areas of interest for this project. NIR spectroscopy's role in the industry is explored in further detail in the following section.

Chapter 2.2: Usage of NIR in Plastic Sorting

One of the objectives is to research to capabilities of resin identification through NIR spectroscopy. NIR is currently used in some recycling facilities, but this project will explore the feasibility of the technique in smaller-scale recycling plants.[47] As mentioned in Chapter 1.5.1, Wu et al. and Zheng et al. had some success in identifying different plastic resins with their NIR and discrimination methods.[13, 48]. Other studies have used NIR to address different problems within the recycling industry. Chen et al. used NIR to identify multilayer plastics, which are commonly used in packaging materials.[72] Multilayer packaging is composed of several layers of different materials, hence the name. Their experiment looked at PET, LDPE, and PP materials due to those resins being a common material. The group compared multilayer and monolayer samples and found that the position of the peaks in the spectra allowed them to differentiate between the sample types. NIR struggles with black samples due to the soot and carbon particles absorbing all of the light in the spectral region that NIR uses.[73] Most conveyor belts are black, which would interfere with transparent samples. Chen et al. accommodated for this by using a dark green conveyor belt in their experiment instead.[72]

Steinhert is one of many manufacturers that provides a variety of automated NIR sorters such as the UniSort PR EVO 5.0®, a machine equipped with AI-supported object recognition that excels in PET bottle sorting.[74] Steinhert also produces the UniSort Black, a NIR sorting unit designed to sort black PVC.[75] NRT, another manufacturer, produces sorters such as the SpydIR®-R and the SpydIR®-T.[76] These products utilize reflective and transmissive technology, respectively, in order to sort PET, HDPE, and remove polymer contaminants. A recycling facility might use multiple sorters as opposed to relying on only one machine. This could make the price of these machines a challenge when it comes to implementing this technology.

The aforementioned equipment is designed to work automatically in recycling facilities. There has also been work in combining manual sorting with NIR sensors. Rani et al. conducted an experiment using a MicroNIR On-Site, a handheld NIR spectrometer.[77] The spectra were saved to a USB, which could then be analyzed on a computer using the MicroNIR™ Pro v3.0 software. Rani et al. found that a small spectrometer would yield spectra to identify all six of the main RIC plastics when PCA and DA analysis was used. Rani et al. believed the experiment had promising results that could lead to the improvement of manual waste sorting. Cross-contamination is a problem in the sorting process, even when using automation, so this combination of manual and automatic sorting technology could be implemented in order to improve the purity of recycled resins.

Chapter 2.3: Materials and Methods

2.3.1: Sample Preparation

A total of thirty-six plastic samples were obtained from household recycling. At least three of every RIC was collected. It was difficult to find household PVC, so several PVC samples were purchased at The Home Depot®. The plastic items that previously contained food, beverages, or soaps were washed with dish soap and hot water for sanitary reasons. This cleaning process also ensured that the insides of the plastic bottles would have no remnant liquids that could interfere with the NIR spectra. Every sample was cut into a roughly 4 cm x 4 cm square. Table 1 contains a list of three samples of each RIC that will be discussed in Chapter 2.4, while a complete list of every sample is provided in Tables A-1 and A-2 in Appendix A. The sample names and resin types are listed. A brief description of each sample is also provided in order to describe their colours and other characteristics. Some of the samples had labelling, which is also included in Table 1.

Table 1: List of samples. Description of each sample and its labelling is also provided.

Sample #	RIC	Sample Description	Label?	Sample colour
#9	1	7-UP® bottle	Yes	Green, transparent
#10	1	Pepsi® bottle	Yes	Clear, transparent. Blue label.
#24	1	Pantene® shampoo bottle	Yes	Opaque, white.
#7	2	Dove® hand soap bottle	Yes	Opaque, white.
#22	2	Tide® laundry detergent bottle	Yes	Opaque, red. Blue and yellow label
#23	2	Ivory® bodywash bottle	Yes	Opaque, white.
#27	3	PVC pipe fragment	No	White
#34	3	PVC stick	No	Opaque, white
#36	3	PVC gutter pipe	No	Opaque, white
#5	4	PC® food lid	Yes	Opaque, light gray.
#16	4	Squeeze water bottle	No	Opaque, red. White logo lettering.
#28	4	Plastic bag	No	Clear. Yellow and white design.
#31	5	Pringles® Snack Stacks cup	No	Opaque, white.
#32	5	Microwaveable food container	No	Opaque, white
#39	5	Microwaveable food container	No	Translucent, red.
#12	6	Plastic plate	No	Opaque, white
#20	6	Tim Horton's® hot beverage cover	No	Opaque, white
#21	6	Activia® yogurt cup	Yes	Opaque, white. Green and white label.

2.3.2: NIR Spectra Acquisition

The spectra were obtained by using a StellarCase-NIR Portable Material ID & Composition Analyzer. The instrument was provided by Direct NutriSciences, a local pharmaceutical company. The StellarCase analyzer operated at an optical resolution of 2.5 nm and was equipped with a tungsten halogen lamp that acted as the reflectance source.[78] The instrument was capable of obtaining NIR spectra between 900-1700 nm. An opening in the instrument contained the lamp and sensors. The opening had a diameter of roughly 3.5 cm, which was the reason why the plastic samples were cut into 4 cm x 4 cm squares. The light hits the sample from below and reflects into the detectors, which means the instrument obtains a spectrum through reflection.

Each sample was placed on top of the opening and scanned in order to obtain a NIR spectrum. Each spectrum was saved and added to a library on the device. The spectral software SpectraGryph v1.2.16.1, created and distributed by Dr. Friedrich Menges, was used to visualize the spectra. The software provided the function of converting each plot into a .png file in order to make presenting the data easier. The SpectraGryph software also allowed for multiple spectra to be overlapped onto one plot.

Several of the samples had some form of labeling on them. These label types included stickers, printed labels, and engraved labels. Any sample with a label had its labeled and unlabeled side measured. These two measurements were denoted as “label” and “no label”. Additionally, the curved samples were measured again as flattened versions. A black object was placed atop the curved samples in order to flatten them. This would allow the sample to sit more level above the opening. Flattened samples were named “f” in order to differentiate them from the non-flattened samples.

Chapter 2.3.3: Unknown Resin Analysis Process

Every sample was saved in the NIR instrument spectral library initially. This was mainly done in order to ensure there was a copy of every sample saved on the equipment. A second library directory was made, which was more curated. The full list of samples used in the filtered library is listed in Table A-1 in Appendix A. Unusable spectra were removed from the library. Those specific samples are listed in Table A-2 in Appendix A. A further discussion on these unusable spectra is available in Chapter 2.4.5. For each of the six resin types analyzed in this project, one sample out of all of the samples that were prepared was chosen via a random number generator. The chosen samples are listed in Table 2. These samples were also removed from the filtered library.

Table 2: Samples used for the resin analysis test.

Resin type	Name of sample used
PET	Sample #9
HDPE	Sample #22
PVC	Sample #27
LDPE	Sample #5
PP	Sample #39
PS	Sample #33

The StellarCase analyzer has the additional function of analyzing a sample and comparing it to the data stored in its library. This function was used to test the device's ability to detect and match samples of the same resin type. This experiment was performed on a much smaller scale compared to how NIR is used in the industry, so this analysis component will model how the NIR sensors would be used in a recycling facility.

Chapter 2.4: Results and Discussion

Chapter 2.4.1: Spectra Results

Each sample was scanned, saved, and the spectrum was viewed through the SpectraGryph program. Three samples for each resin type were chosen and overlapped onto one plot. The spectrum for each resin type can be seen in Figures 10-15. Any sample with a label was also included in the resin spectrum. An individual spectrum for each sample can be found in Appendix B.

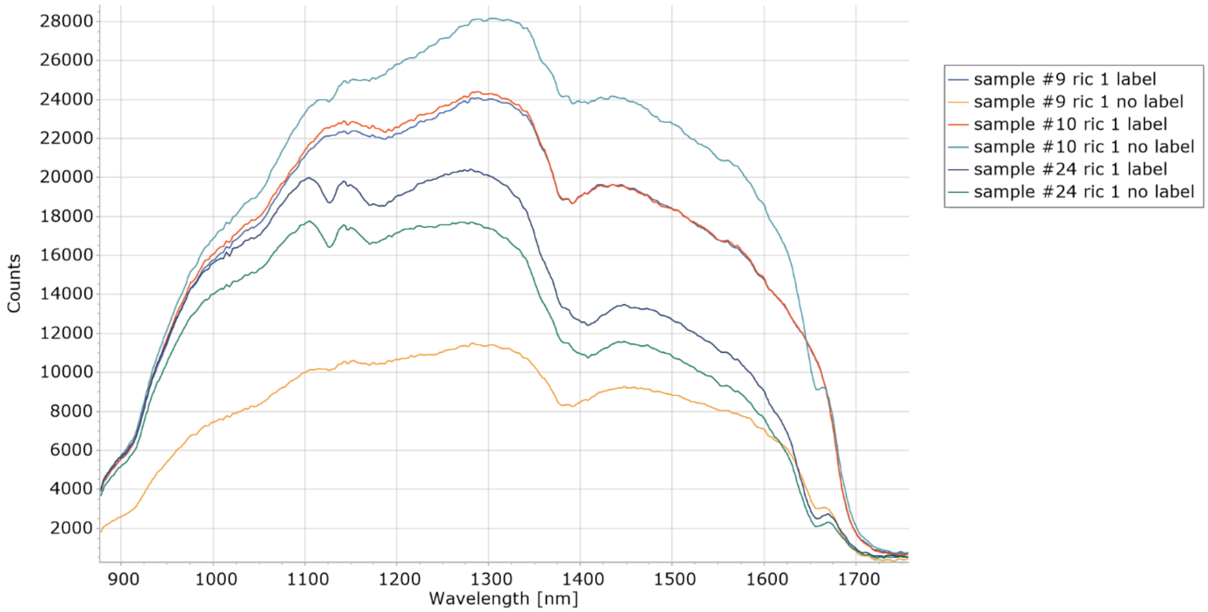

Figure 10: PET NIR plot of the spectra for Samples #9, 10, and 24

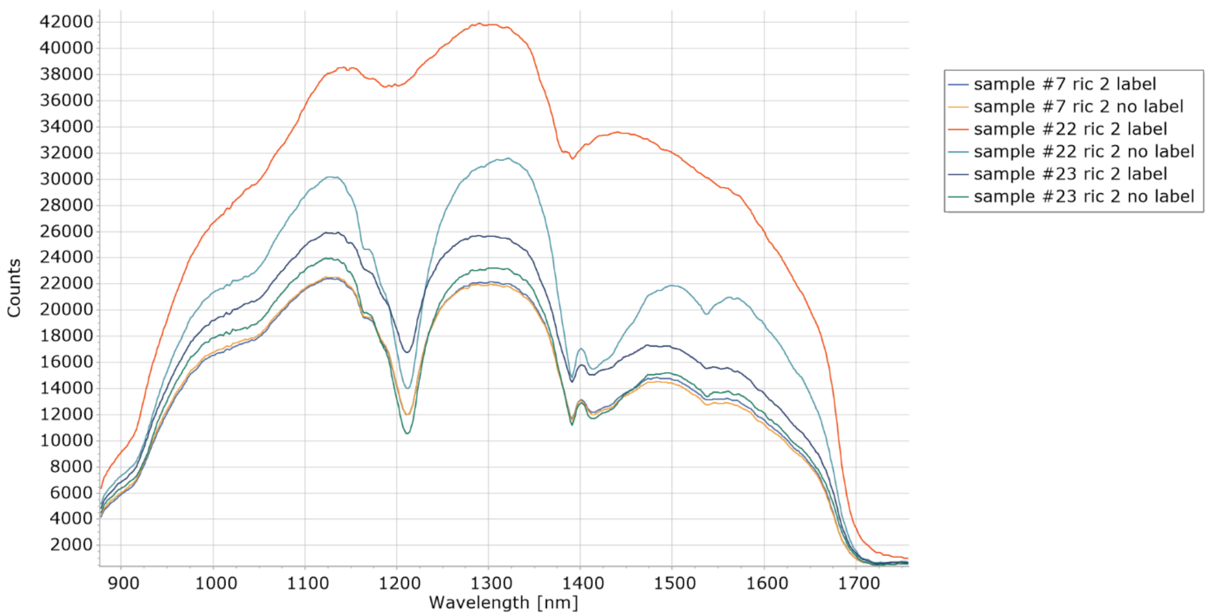

Figure 11: HDPE NIR plot of the spectra for Samples #7, 22, and 23

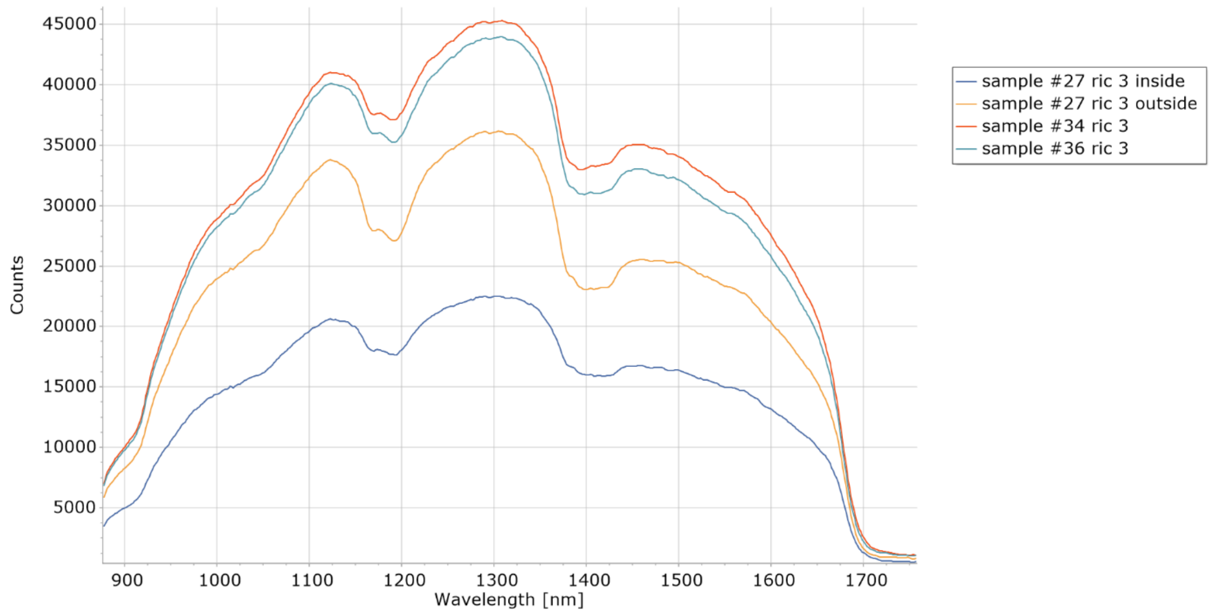

Figure 12: PVC NIR plot of the spectra for Samples #27, 34, and 36

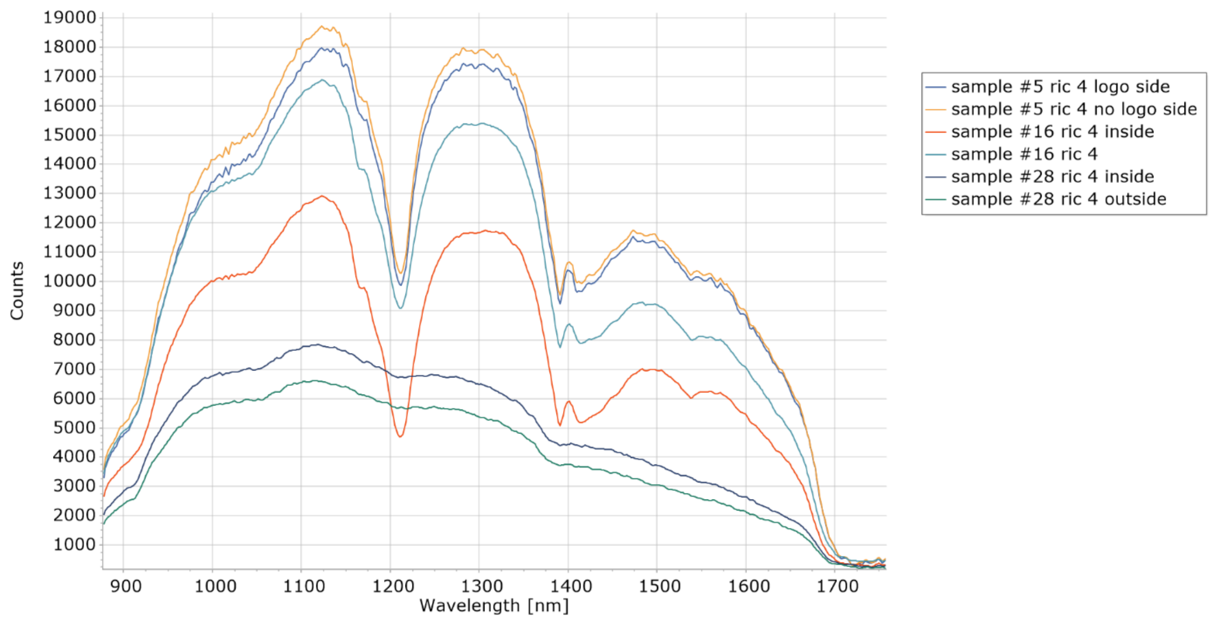

Figure 13: LDPE NIR plot for the spectra for Samples #5, 16, and 28

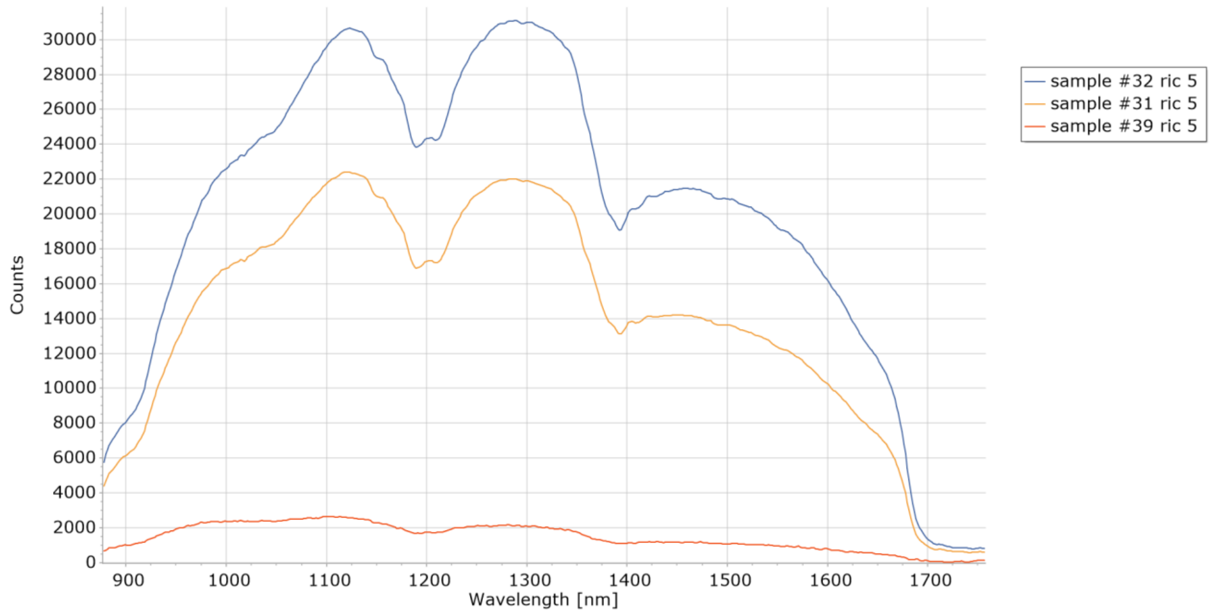

Figure 14: PP NIR plot of the spectra for Samples #31, 32, and 39.

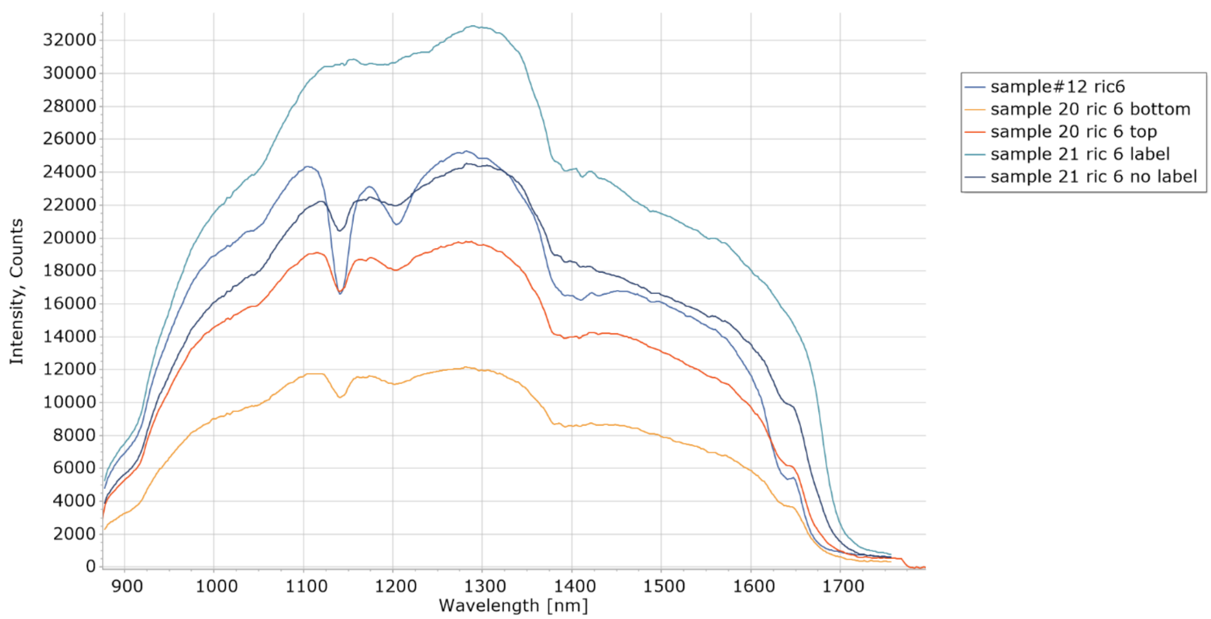

Figure 15: PS NIR plot of the spectra for Samples #12, 20, and 21.

Each plot measures the intensity counts and wavelengths from the reflected light on each sample. Each plot had a series of peaks and valleys as the intensity changed as the wavelength increased. For samples of the same resin type, the peaks and valleys occurred at roughly the same wavelengths. The main difference between the same-resin samples was the intensity count. For example, each spectrum in Figure 11 followed a similar trend in having a sharp decrease in intensity at around roughly 1200 nm. However, Samples # 7 (no label) and #22 (no label) have a difference of roughly 2000 intensity counts between the highest points for each spectrum.

The plots showcase the key differences between the six main RIC plastics. Both the HDPE and LDPE plots in Figures 11 and 13 have a similar shape. They both experience a significant drop in intensity at roughly 1200 nm. The other plastics experience a drop in intensity around this same wavelength, too, but not to the same extent which distinguishes RIC #2 and #4 plastics from the others. Both of these plastics are derived from ethylene, so it is expected that their plots are similar. For the most part, the HDPE and LDPE spectra followed the same trend. The exception was Sample #28, which was a plastic bag for bagels.

There were difficulties with both sides of Sample #28. The sample was chosen because research suggested that plastic bags for baked goods can be made from either LDPE or PP, which was why the bag was initially classified as LDPE.[79] The spectrum for this sample revealed that resin type in the sample is unknown. The sample could be made from LDPE and plasticizers, which caused it to look so different compared to the other LDPE samples. The sample also might have been made from PP, but it is not clear.

The aromatic plastic resins, PET and PS, could be differentiated by their smaller peaks in the spectra. There are two jumps in intensity between 1100-1200 nm. PVC and PP, meanwhile, had different spectra compared to the other four plastics. The two plastics had similar plots, but the PVC samples tended to have larger intensities in comparison to the PP samples. This could have been caused by the chlorine atoms that are included in the structure of the PVC samples.

Chapter 2.4.2: Effects of Labels

In VanLeeuwen's research, the effect of labels on the spectra was an area of interest.[52] FTIR had struggled with reading the sample through the label, while Raman spectroscopy produced a combined spectrum of the sample and label material. For the NIR spectra obtained from this experiment, the labels on the spectra seemed to have varying impacts on the spectra results. In Figure 10, the labeled and unlabeled sides of Samples #9 and #10 had different peak shapes and intensities. However, Sample #24 in Figure 11 produced very similar spectra from both sides. In Figure 11, the HDPE samples and their labels all produced similar plots with the exception of Sample #22.

The Association of Plastic Recyclers (APR), an international company that represents the plastic industry, provides a design guide for companies about labels.[80] The APR explains that some companies use labels that cover the product and interfere with a NIR sensor's ability to read the polymer type. This problem often occurs with shrink sleeve labels that cover the whole product. The APR's Design® Guide for Plastics Recyclability suggests that companies should use labels that only cover 75 % of the product's surface. Therefore, labels can be an issue in characterization of plastics through NIR sensors. The sensor used in this experiment had a small opening to measure the samples, which would make it difficult to avoid scanning the label. If the opening in the instrument had a larger diameter, or a different instrument was used altogether, the spectra for both sides of the samples could have been more similar.

Chapter 2.4.3: Effects of Colour on NIR Spectra

The samples gathered for this experiment came in a wide variety of colours such as white, red, black, green, brown, light gray, and clear plastics. The labels on some of the samples were coloured blue, yellow, and other colours as well. The samples were gathered with colour variety in mind in order to determine how the spectra would appear for similar resins with different colours. For the lighter coloured samples, the different spectra had no drastic differences. For example, in Figure 13, Sample #5 was light gray, and Sample #16 was red. Despite their colour differences, both samples had the same peaks at the same wavelengths. The only difference was the values of the intensity. A difference in intensity occurred even for samples of the same colour and RIC such as Samples #20 and the unlabeled side of Sample #21. Therefore, the differences between the spectra of the light-coloured samples could have been caused by other factors.

The colouring of the sample only had a significant impact on the spectrum when the sample was black. The carbon and soot that contribute to a sample's black colouring absorb the light in the NIR region.[73] If the sample isn't reflecting light, then the detectors inside the NIR instrument cannot sense the sample as efficiently as it could for a light sample. This resulted in a noisy and unusable spectrum. This problem also occurred for the clear plastics with the exception of those with coloured labels.

Chapter 2.4.4: Library Analysis Results

The spectral library was initially tested with every sample that was prepared. When a sample was analyzed, it matched with the library file of itself. While this showed that the library could correctly identify a sample to itself, the method didn't allow for comparisons between samples of the same RIC. The samples would have multiple "hits" in the library, but only a small number of composition matches were provided. This initial library also contained the noisy spectra, which matched to other noisy spectra.

After filtering the initial NIR spectral library, forty-nine samples remained. The list of samples used in this curated library can be found in Table A-1 in Appendix A. Each sample from Table 2 was measured once again and was compared to this filtered library. The instrument states how many items were in the library and how many hits the sample made.

Table 3: Results of spectral library analysis.

Sample name	RIC #	Closest matched sample name	Correlation of closest sample	RIC # of closest matched sample
Sample #9 (label)	1	Sample #10 (label)	0.84	1
Sample #9 (no label)	1	Sample #10 (no label f)	0.84	1
Sample #9 (label f)	1	Sample #10 (label f)	0.88	1
Sample #9 (no label f)	1	Sample #10 (no label f)	0.88	1
Sample #22 (inner side)	2	Sample #16 (outer side f)	0.94	4
Sample #22 (label side)	2	Sample #10 (label)	0.87	1
Sample #27 (outer side)	3	Sample #36	0.88	3
Sample #27 (inner side)	3	Sample #36	0.88	3
Sample #5 (no logo)	4	Sample #7 (no label)	0.89	2
Sample #5 (logo)	4	Sample #7 (no label)	0.90	2
Sample #39	5	Sample #14 (both sides)	0.67	5
Sample #33	6	Sample #20 (top and bottom)	0.84	6

For a majority of the samples in Table 3, the analysis test matched them to a sample of the same RIC. The exceptions to this were Samples #22 and #5, a HDPE and LDPE sample respectively. The label-side of Sample #22 matched with Sample #10, which was a PET bottle.

The opposite, unlabeled side of Sample #22 matched closest to Sample #16, an LDPE bottle. The correlation to the LDPE sample was a reasonable result because of the similarities HDPE and LDPE have. The structure of Sample #22 was most likely similar to that of Sample #16's. For Sample #5, both sides of it matched the HDPE Sample #7. These samples most likely matched to each other for the same reasons that Sample #22 and Sample #16 matched. The label of Sample #22 matching with the PET Sample #10 was not expected. The overlap between these two samples can be seen below in Figure 16.

Figure 16: Spectrum overlap of the labeled sides of Samples #10 and 22.

The above plots showcase how both Samples #10 and 22 follow a similar trend in wavelengths and intensity peaks. The shape of the Sample #22 plot looks more in line with the PET plots in Figure 10 than any of the PE plots. The results from these spectra would suggest that the label on Sample #22 is comprised of the same material that was used to create the label on Sample #10. It was unclear if these labels were made PET or a different material. The other side of Sample #22 matched with an LDPE sample. This meant that the light did not penetrate through the label and the sensor picked up the label's reading instead when the label side of Sample #22 was scanned.

Almost all of the analyzed samples had a match with a correlation percentage of at least 84 % with the exception of Sample #39, which only had a 67 % match to Sample #14. Both the inner and outer sides of Sample #14 had the same percentage match to Sample #39. Figure 17 located below contains the overlap of these two samples.

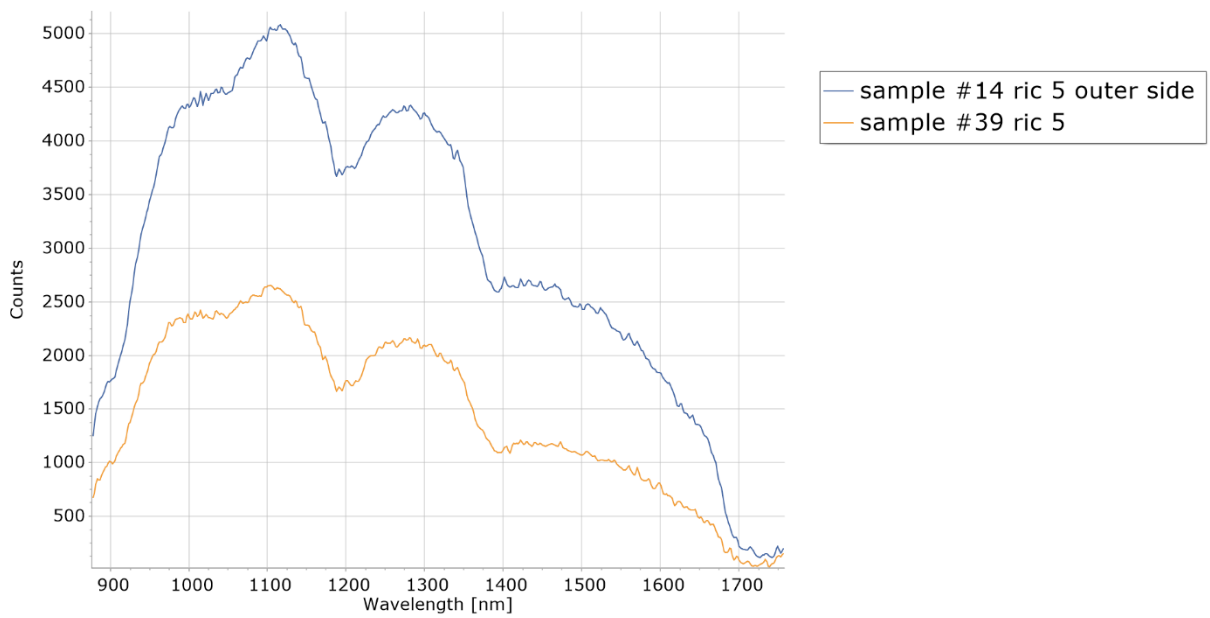

Figure 17: Spectrum overlap of Samples #14 (outer side) and #39.

The two spectra from the samples in Figure 17 look similar, but their correlation values don't agree. Sample #14 was transparent with a red logo printed on it, while Sample #39 was red and slightly translucent. Transparent samples proved difficult to scan, which will be discussed in further detail in the next section. The transparent samples didn't provide as clear of a spectrum compared to the opaque samples. The two spectra overlapped in Figure 17 had some noise in their baselines, which gave the spectra their slightly spikey appearance. This issue only appeared for the transparent PP samples because the Samples #31 and 32 spectra in Figure 14 were opaque and thus gave spectra with better readability. The correlation of 67 % indicated that the NIR analyzer couldn't identify the PP samples as effectively as the other plastics.

The other five plastics had much stronger correlations to the library samples, but only one of them attained a match of 94 %, which was Sample #22 matching to Sample #16. This high value would indicate a strong match between the composition of the two items. In comparison, the other samples would be slightly less accurate matches. In summary, the NIR analyzer yielded stronger correlations for the HDPE and LDPE samples. However, it couldn't differentiate between the different density PEs. PET and PVC were the next most accurately matched plastic types. The PS samples were slightly less accurate, and the PP sample was the least accurate resin type to match with the library.

Chapter 2.4.5: Unusable Spectra

As mentioned in the analysis of the spectral library test, several samples had to be removed from the library. This was due to the fact that the samples were unusable and had no observable signals. During the preliminary resin analysis tests, the illegible-spectrum samples would match to other noisy spectra even though the samples were marked with different RICs. These samples were removed from the spectral library for the final test described in Chapter 2.4.2. This was done so that composition matches would be as accurate as possible.

These illegible samples were noticeable prior to saving the spectrum. When scanning a sample, the "run" button needed to be clicked, followed by the "capture" button. When the sample was running, the intensities on the spectrum would fluctuate in real-time and would appear as if they were vibrating. The capture function stopped the detectors and gave a freezeframe of the spectrum. For some samples, the spectrum fluctuation wasn't noticeable, and the captured image of the spectrum would maintain a consistent shape. However, for some samples such as Samples #2, 3, and 11 in Figure 18, the spectrum drastically fluctuated and had a spiky appearance.

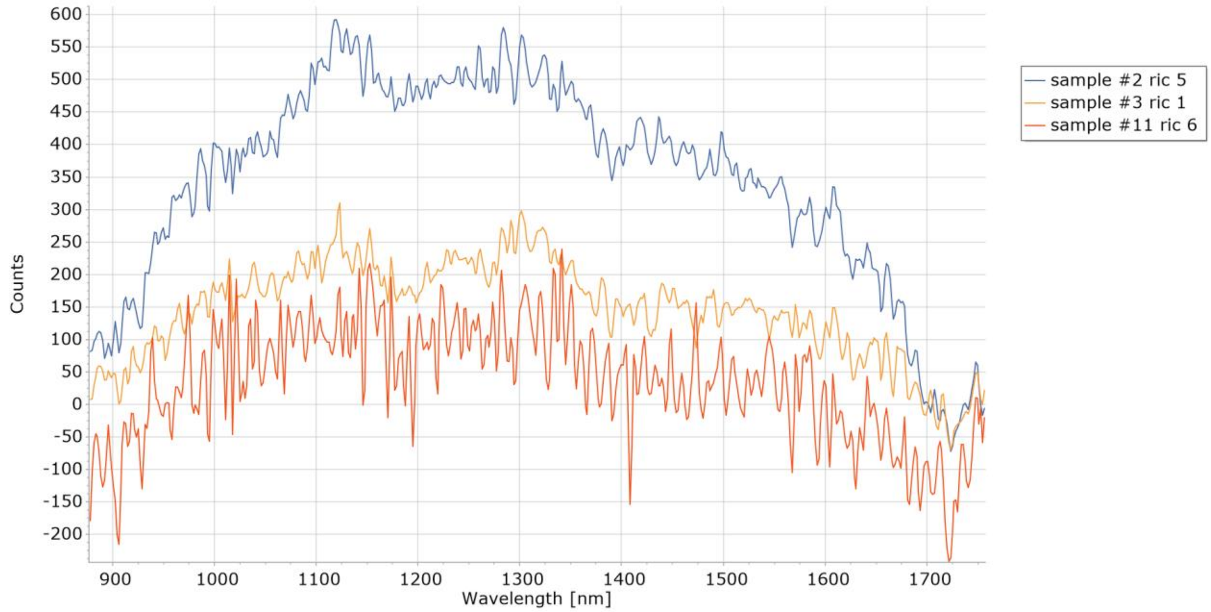

Figure 18: The captured spectra of Samples #2, 3, and 11 overlapped with each other. Each sample is made from a different resin type.

The three samples in Figure 18 were difficult to read. Their spiky peaks make it difficult to determine which wavelengths experience an increase or decrease in intensity. The highest observed intensity was almost 600 counts for the PP Sample #2. In comparison, the three PP samples in Figure 14 all had much higher intensities. Additionally, these illegible spectra had negative intensities at certain wavelengths.

An illegible spectrum occurred when the sample in question was either black or transparent. These results were expected for the black samples because of the knowledge that

NIR struggles with dark colours.[73] The NIR instrument measured the samples through reflection, so it made sense that it struggled with the black samples that were absorbing the light. However, these results were not expected for the transparent samples. Other studies such as those by Chen et al. and Rani et al. did not have these issues when they used NIR on transparent samples.[72, 77] Chen et al. had even used a different coloured conveyor belt and a reference spectrum of the belt's surface in order to get a better reading of their samples.[72] The sensors in the analyzer used in this experiment couldn't detect the open air above the opening during the time it took to switch samples. This meant it wasn't the background causing this issue. Therefore, this could have been an instrument-specific issue or an issue of the thickness of these transparent samples.

Chapter 2.4.6: Comparison of Spectroscopy Techniques

The NIR analyzer had varying accuracy in identifying the different plastics. The correlation values suggest that some plastics were easier to identify compared to others. Now, this accuracy needs to be compared to other spectroscopic techniques in order to see which method could be most effectively implemented in PEI. VanLeeuwen's project with FTIR spectroscopy involved correlation tests for different spectral regions.[52] The three spectral regions VanLeeuwen examined were 2800-3000 cm^{-1}, 1300-1550 cm^{-1}, and 700-900 cm^{-1}. The mean correlations for all of the plastics were 95.41 %, 97.42 %, and 90.79 %, respectively. Additionally, VanLeeuwen tested how a sample would correlate to reference samples of different resin types in the 1300-1550 cm^{-1} region. For most of the resin types, the sample would match to its correct reference RIC plastic with a correlation of at least 90 %. The exceptions to this were HDPE and LDPE because they had high correlations to each other.

Overall, VanLeeuwen's portion of this long-term project found that FTIR could accurately match samples to the correct resin type.[52] It's important to also consider the downsides of FTIR when comparing it to NIR. Labels were a detriment to the ability of FTIR to produce a spectrum, while labels did not make a huge impact for most cases with NIR. VanLeeuwen had also observed that colour affected the spectra obtained from Raman spectroscopy. Colours didn't make a big impact on the NIR spectra either, which indicates that NIR is more suitable for diverse plastic colours and labels.

VanLeeuwen's project didn't test the correlation matches for Raman spectroscopy.[52] Other research groups, however, have examine the capabilities of Raman spectroscopy in plastic sorting and identification. Tsuchida et al. created a Raman-based sensing apparatus for a recycling facility that was able to identify shredded plastics.[81] The group found that by preprocessing their Raman signal, the identification accuracy would reach 94 %. Another study by da Silva et al. utilized Raman spectroscopy in order to sort HDPE and LDPE from a collection of other plastics.[82] A combination of Raman scattering measurements and predictive methods was effective in separating the two PE plastics from other contaminants. This was something that NIR struggled to differentiate. The HDPE samples matched to LDPE samples and vice versa.

In order to fully understand the accuracy of the results from this project, the NIR analysis test results need to be compared to the NIR results obtained from other research groups. The study by Zheng et al. was able to identify PE and RIC #1, 3, 5, and 6 plastics effectively by using a discrimination model.[48] The system could identify unknown samples with 100 % accuracy. Chen et al.'s study with LDPE, PP, and PET could correctly match the correct resin at an accuracy of 95 % and higher.[72] Another study by Wu et al. worked with PP, PS, and several other plastics found their NIR auto-sorter to have an overall 95 % sorting accuracy.[13] These three studies mentioned all had accurate matching results with their NIR setups. Therefore, there is evidence to suggest that NIR should accurately identify different plastics. The results from this project had noticeably less accurate analysis tests. If other researchers could obtain more accurate results with the same spectroscopic method, then this accuracy difference could have been caused by the equipment, methods, or library used in the project.

The StellarCase Portable NIR Analyzer operated through reflection. The studies previously mentioned were all performed in recycling facility-like conditions with the use of conveyor belts and overhanging NIR sensors.[72, 76] In these studies, the light source will pass through a sample, hit the conveyor belt, and then reflect back through the sample and hit the NIR detector(s). This set up means that these researchers used the transflection measuring method. This method seemed to help the researchers detect transparent samples with no issue. The curvature of the samples also didn’t seem to be an issue for the other researchers. However, these two conditions were a struggle with the StellarCase Analyzer used in this project.

Another issue to examine is the analysis test accuracy. The previously cited studies all had very accurate identification results. The differences in the results in this project compared to the other studies could have been caused by the usage of the spectral library. The spectral library used in this project contained forty-nine samples. Some of these samples included the labeled and non-labeled sides of the same item. In this project, at least three of every RIC plastic was gathered. It was difficult to gather some of the plastics such as PVC and LDPE in household waste, which was why some additional samples had to be purchased. The samples in Table 2 were removed from the library, otherwise they would have only matched to its identical spectrum. This meant that for some plastics, there were only two reference samples in the spectral library.

Most spectral libraries that can be purchased for structural analysis use contain numerous samples. For example, Kaplan Scientific provides many databases containing thousands of spectra to assist researchers in their studies.[83] They offer databases for specific applications such as polymer or hazardous substance identification. This project operated at a much smaller scale compared to how NIR is used in the recycling industry. A recycling facility most likely would purchase a spectral library database for their NIR sensor as opposed to creating one like what was done in this project. The less accurate results in this project could have been caused by the small library that was created. If a recycling facility were to implement a NIR sensor system, the spectral library would be purchased from a provider, and it would contain a much larger number of high-quality spectra.

Chapter 3: Automated Colour Sorting

Chapter 3.1: Usage of Colour Sorting in Plastic Recycling

Colour is another factor used to sort plastics in the recycling industry. Colour sorters currently see some use in the recycling industry. According to the literature search by Lubongo et al., colour separation can be performed by using either optical sorters or AI.[47] One example of a manufacturer that provides these optical colour sorters is Hefei Angelon Electronics.[84] The company produces Angelon Plastic Color Sorters, which are used in some recycling facilities. Their equipment is designed for use with numerous plastics such as PE bottle caps, PET or PP bottle flakes, and other colourful plastics. This specific sorter is equipped with certain equipment such as light emitting diode (LED) lights and charge-coupled device (CCD) high-definition (HD) cameras.[85] The CCD cameras view the plastic samples, and the LED lights allow for a high-quality capture of the sample. The use of colour sorters such as these can assist with the removal of impurities in the recycling stream in facilities.[84] Hefei Angelon Electronics states that their high-capacity models can reach sorting accuracies up to 99.99 %. The A221C4-128V6 and A421C8-256V6 sorting models produced by Hefei Angelon Electronics have sorting outputs of 0.5-1 and 1.0-2.0 tonnes per hour respectively.[85]

Colour sorters have also been used in combination with other sorting methods throughout the industry. The literature review by Lubongo et al. found that there are twenty-two optical sensors on the market that can sort plastics by their colour.[47] Some of these manufacturers include Eagle Vizion, RTT Steinert GmbH, and NRT. Steinert and NRT were previously mentioned in Chapter 2.2 because they also produce NIR sorters in the industry. The Aquila Series made by Eagle Vizion utilizes NIR sorting technology, but it is also capable of sorting colourful plastics. The equipment exhibits an overall accuracy of 90 %. Steinert builds the Unisort P4000, which utilizes both NIR and vision spectroscopy. This allows the machinery to also sort 2.5-4.0 tonnes plastics of plastic per hour based on their colouring with a 99 % accuracy. The third sorting example, the MultiSort ES made by NRT, is a vision-based plastic sorter that can sort 5.5 tonnes per hour with a sorting accuracy of 95 %.

Two out of the three examples of colour sorters given operate using visible spectroscopy. This form of spectroscopy can identify the colour of a plastic sample by comparing it to the visible spectrum light.[47] This extra function allows the Unisort P4000 and MultiSort ES to be able to sort colourful plastics including black samples. This is especially important due to the issues of NIR sensors being unable to detect black samples, which was observed in this project.

In a similar fashion to the NIR portion of this project, colour sorting technology will be explored on a small scale. IWMC relies on manual sorting of plastics, so an automated system could streamline the recycling process in PEI.[12] By doing so, more plastics that enter these facilities can be sorted and recycled, when they otherwise might not have been. Colourful plastics aren't usually considered for recycling due to manufacturers not finding them desirable.[11] Colourful plastics are usually sorted in order to exclude them from the recycling stream. However, by improving the overall sorting and recycling process, the number of colourful plastics that actually get recycled could be increased.

Chapter 3.2: Colour Sorting Apparatus Setup

This portion of the project was performed in collaboration with Dr. Nadja Bressan of the University of Prince Edward Island Faculty of Sustainable Design Engineering (FSDE) and the students from her "Mechatronic System Integration" course. The engineering students had access to an automated sorting system that could sort samples based on characteristics such as their colour. This led to the collaboration with the engineering students. A photograph of the sorting apparatus can be seen below in Figure 19.

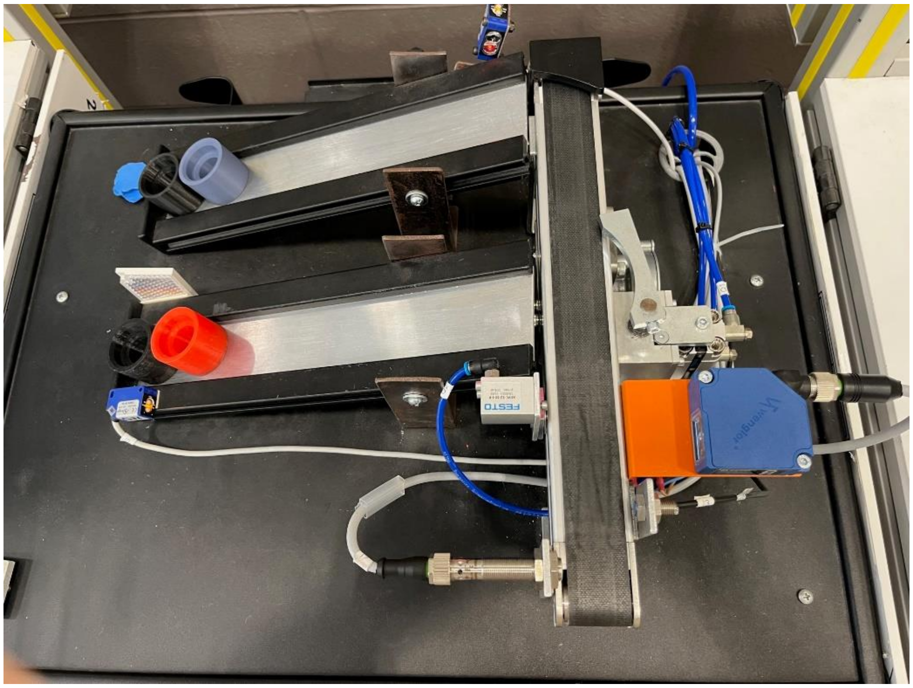

Figure 19: Photograph of the colour sorting apparatus

The sorting device was set up on a conveyor belt with two ramps that separated the samples into two groups. At the front end of the conveyor was a capacitive sensor. This sensor would detect if an object was placed in front of it. If the sensor detected anything, it would signal the motor memory to activate and move the belt.

A Wenglor Color Sensor, which can be seen in Figure 19, was attached to the sorting apparatus. This sensor allowed for three inputs to be coded into it. The sensor would read the reflection given off when a light would hit the sample as it passed through the system. The sensor would detect which of the three inputs it was reading, and the system would act accordingly. Due to there only being three inputs available on the colour sensor, only three colours can be examined at a time. The code can be changed to swap out the colours, but the code for the whole setup needed to be changed even if only one colour is swapped out. This means that there would be additional time needed to switch the code and that sorting tests wouldn't be as fast.

The gray structure opposite to the colour sensor contained a pneumatic short stroke. When the capacitive sensor detects a sample placed in front of it, the short stroke would stick out. This stroke would stop the sample as it reached the light from the colour sensor. This structure was added to the colour sorting system in order to slow down the sample. This allowed the colour sensor enough time to read the sample before it passed by. The output for the colour sensor was connected to the pneumatic arm. One of the three inputs being measured would be chosen to act as a signal for the arm to move. If activated, the pneumatic arm pushes the sample down the first ramp. The other two inputs will not activate the arm and will instead move down the belt and slide down the second ramp. The small blue sensor attached at the second ramp seen in Figure 19 is a photoelectric sensor. This will detect motion as a sample moves down either ramp. Any motion picked up by this sensor will trigger the pneumatic arm to reset if necessary. After the arm resets, another sample can be analyzed. This process was designed to be fully automated.

Chapter 3.3: Colour Sorting Sample Preparation

The plastic samples were prepared by cutting and forming them into cylindrical shapes by using hot glue. In order for the samples to fit into the conveyor belt, they were cut to have a height of roughly 1-1.5 cm and a maximum width of 3 cm. The following colours were used for the sorting test: white, black, green, red, brown, and dark blue. Some of the plastics used in the colour sorting test were obtained from the leftover samples from VanLeeuwen's work.

Additionally, some manufactured samples used in previous engineering students' projects were also used for this project. These samples can be seen in on the two ramps in Figure 19. The material that these samples were made out of was unknown, but that information wasn't necessary for this portion of the project. The photograph shown in Figure 20 showcases some of the plastics samples that were prepared for the colour sorter.

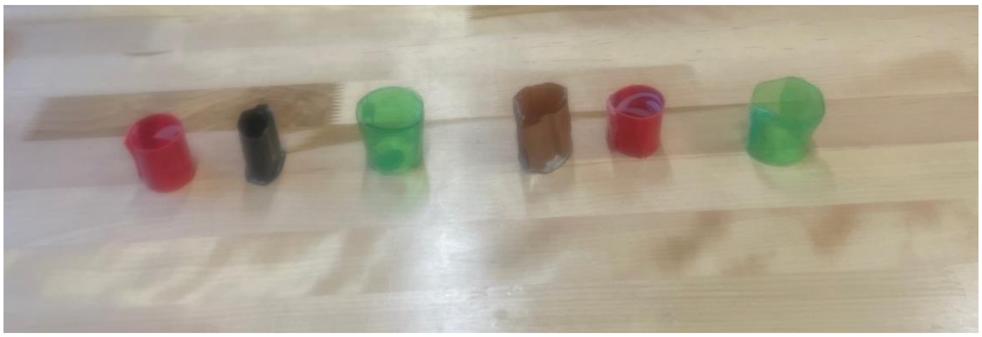

Figure 20: Photograph of several plastics samples used in the colour sorting test.

Chapter 3.4: Colour Sorting Results and Discussion

Chapter 3.4.1: Colour Sorting Observations

Two tests were performed with the colour sorter. The first test used red, black, and dark gray as the three inputs. Black was set as the input to activate the pneumatic arm. Three samples, one of each colour, were tested several times and every time the black sample was successfully separated from the other two samples. The second test used white, red, and black samples. The black samples were chosen as the input linked to the pneumatic arm. Once again, the sensor was able to differentiate between the three colours and the pneumatic arm activated to separate the black samples. The pneumatic arm worked for the correct colour, however, there were inconsistencies with the colour sensor which will be discussed.

Chapter 3.4.2: Colour Sensor Inconsistencies

When the sorting apparatus was being prepared, there were inconsistencies with the colour sensor. First, there were difficulties with making the colour sensor read the three inputs. The system was fixed and was successful for the first sorting test. The first test was done with the samples that the engineering students designed the whole project around. However, the colour sensor began to experience inconsistencies in the second sorting test.

When a sample approached the colour sensor, it was stopped by the pneumatic short stroke. Normally, the short stroke would revert to its original position once the colour sensor determined the input. Instead, the short stroke remained in place and blocked the plastic sample from passing through. This therefore prevented the sample from being sorted. There were instances where the sample successfully passed by the sensor and into the expected ramp, but it couldn’t be replicated with every attempt.

This inconsistency could have been caused by the different materials and surfaces of the plastic samples. The sensor worked with 100 % accuracy when using the manufactured samples but struggled with the plastic samples from this project. The material and surface of the samples could have contributed to this problem. No other sorting tests were performed due to the time required to adjust the code and the likelihood that the same problem would occur with the samples.

Chapter 3.4.3: Analysis of Sorting Accuracy

The two colour sorting tests had varying results. The first test showcased 100 % accuracy in separating the black samples from the other samples. The second test, as mentioned, was inconsistent. When the sensor worked, it was 100 % accurate. There were other times when the sample couldn't be read and couldn't continue down the conveyor belt. Colour sensors are designed to compare the colour difference (ΔE) between the samples and the colour inputs stored in its code.[86] Some colour sensors on the market operate with a 0.8 ΔE, which allows for a 100 % accuracy.

The Wenglor sensor correctly sorted the plastics in the first attempt, which meant it was operating at industry standards. The second attempt technically was 100 % accurate when the sensor worked. The inconsistency only occurred with the plastic samples, so the sensor must have had problems with detecting them. As previously mentioned in Chapter 3.4.2, this could have been caused by the material type or the way in which the plastic surfaces reflected light. In a recycling facility setting, stronger and multiple colour sensors would likely be used. This would allow more samples to be measured at once. The current setup in Figure 19 only allows for one sample to be measured at a time. This portion of the project and the literature review by Lubongo et al. showcased that there is technology available that could be implemented by the IWMC in order to improve the colour sorting, and recycling in general, in PEI.[47]

Chapter 3.4.4: Sample Preparation Challenges

The samples used in this test needed to fit the dimensions of the conveyor belt and be tall enough for the light from the colour sensor to reach them. This therefore limited the types of plastics that could have been used in this portion of the project. In the early stages of the colour sorting project, a robotic arm in the engineering department was going to be used to place the plastic items onto the conveyor belt. The photograph in Figure 21 showcases the robotic arm and some of the manufactured samples. The grabber was too big for most of the plastic samples obtained in this project. Those that did fit in the grabber couldn't be secured tightly and would slide out of the machine’s grip. Therefore, this aspect of the plastic colour sorting apparatus was dropped from this project and the plastics were placed on the belt manually.

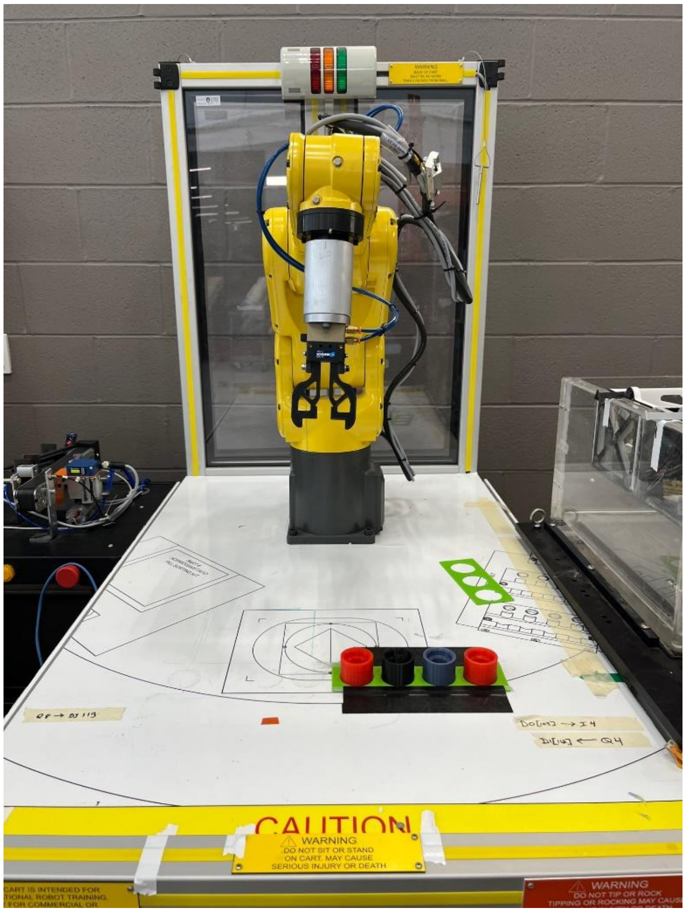

Figure 21: Photograph of the robotic arm used to pick up plastic samples.

There were additional challenges associated with the plastic samples during the sorting test. The conveyor belt and slopes on the apparatus were originally designed for the smooth, cylindrical samples seen in Figures 19 and 21. The samples obtained from the plastics used in this project had rough edges due to them being cut and glued together. This uneven surface on the bottoms of the samples caused them to get caught on the conveyor belt. When the sensor successfully worked, there wasn’t a guarantee if the sample would make it down the ramp. When this happened, the sample needed to be pushed down manually. This caused the whole system to be less automatic than what was expected.

The sorting apparatus could have been adjusted in an attempt to address the issues observed in the experiment. However, these adjustments weren’t made due to the labour action that had occurred on the campus. The design of the sorting apparatus can be examined in further detail in the future, as well as the different colour input combinations that weren’t tested.

Chapter 4: Future Work

Chapter 4.1: Further Colour Sorting Work

Due to unforeseen circumstances, the colour sorting tests weren't able to look at as large of a variety of colours as was planned. The issues that prevented the detector from detecting the colours also weren't able to be addressed due to the time constraints caused by labour action on the campus. Therefore, the colour sorting technology could be examined in further detail.

For both of the two sorting trials that were performed, black was set as the input that activated the pneumatic arm. The code needed to be rebuilt when one of the colours was swapped, so that's why this input was kept the same. However, different colours should be tested in order to determine if the sensor can detect them. The sorting apparatus demonstrated that it could sort black plastics from other colourful plastics, but its overall effectiveness still needs to be determined. Additionally, further experimentation would assist in determining the exact reason why the sensor struggled to detect the samples. By doing so, adjustments could be made to the sorting apparatus which could improve the overall sorting efficiency.

Chapter 4.2: Determining the Composition of RIC #7 Plastics

The results from this project found that NIR spectroscopy can differentiate between the main six RIC plastics based on whether the structure contained PE or an aromatic ring. Spectral libraries can then be used to further identify the plastics such as PET or PS that share similarities in their structures. #7 plastics weren't a large focus for the NIR spectroscopy test because their structures are unknown. Spectral libraries couldn't be used for #7 plastics because there was no guarantee that the gathered samples would be composed of the same materials.

If #7 plastics could be identified, it would open up new markets for the recycling of these plastics. Spectroscopic techniques could be used in order to do so. A preliminary experiment was performed using attenuated total reflection (ATR)-FTIR on a #7 water bottle. A section of the bottle was cut by using a power tool. The spectrum of the water bottle can be seen below in Figure 22. The significant peaks on the spectrum were labeled as well.

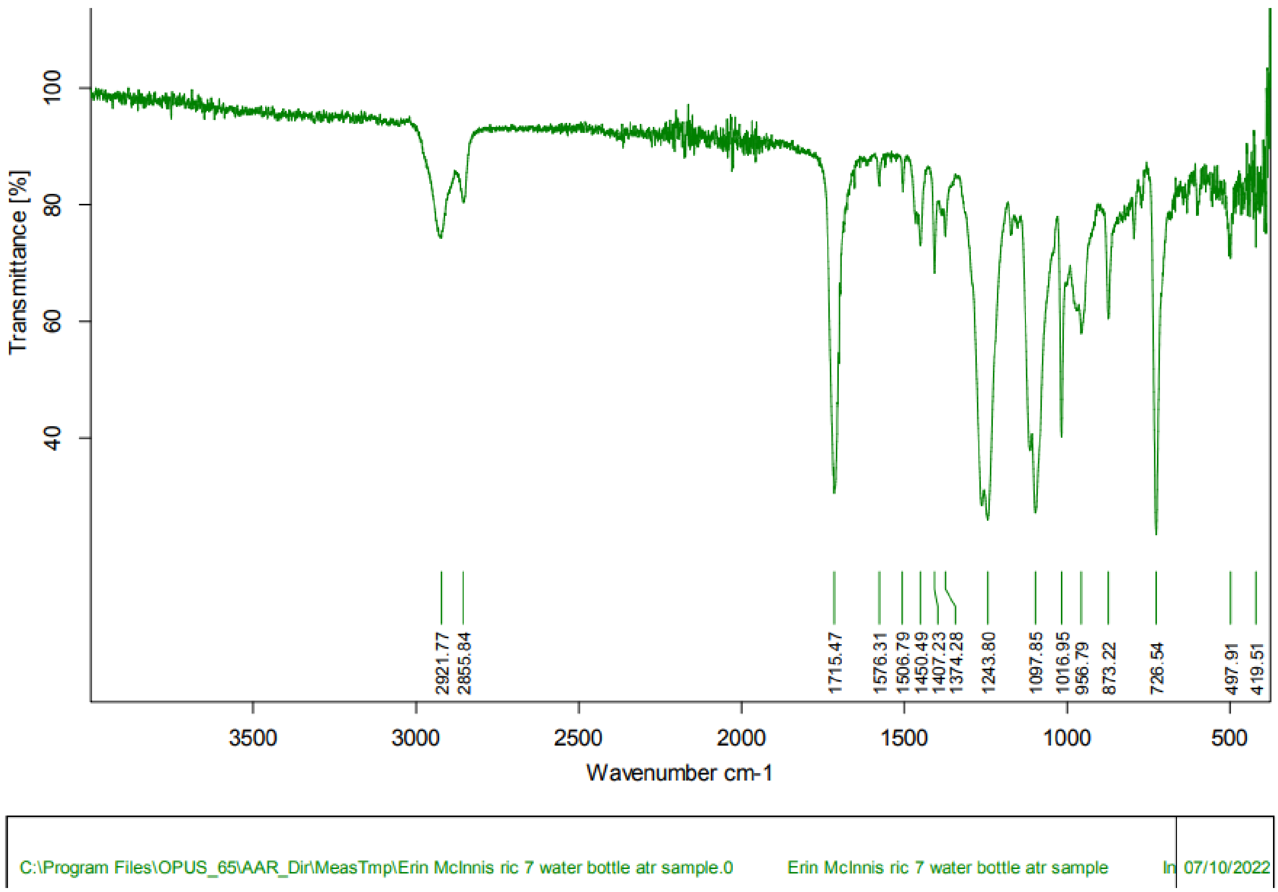

Figure 22: ATR-FTIR spectrum of a RIC#7 water bottle.

The spectrum in Figure 22 showcases the many vibrations in the bonds of the sample. The peak at 1715.47 cm^{-1} indicated that the unknown RIC #7 plastic contained a carbon-oxygen double bond in its structure. The specific wavenumber indicated that the bottle contained either an ester or aliphatic ketone.[65] Several RIC #7 plastics were discussed in Chapter 1.4 and this spectrum could indicate that plastic bottle was made with polyester. This spectrum is very similar to a published spectrum of polyester, which supports the theory that the water bottle was made from polyester.[87]

This shows that FTIR, and possibly NIR, could be used in order to determine the composition of RIC #7 plastics. These plastics aren't accepted by the IWMC in PEI, but an ability to sort these plastics could open the door for new markets.[12] This could therefore help advance the Etkin group's overall goal to improve the recycling process in PEI.

Chapter 5: Conclusion

After completing the NIR tests, a total of thirty-six plastic samples were scanned and compared with one another. Similarities between some of the plastics were observed, which helps to differentiate between them. The aromatic rings in both PET and PS differentiate plastics made from these materials from those made from PE. All six of the main RIC plastics followed similar trends. For example, all six plastic types experienced a drop in their intensity counts at around 1200 nm. However, the value of intensity peaks and decreases differentiated the different plastics.

This project was also performed in order to compare the advantages and disadvantages of NIR in comparison to FTIR and Raman spectroscopy, which were previously tested in the Etkin research group. Factors such as colours and the presence of labels were considered when gathering and measuring the different samples. The colours of the plastic samples did not affect the NIR spectrum, with the exception of black samples. Samples of the same resin type and colour experienced differences in the intensity counts, and samples of the same resin but different colours experienced changes in intensity as well. Therefore, the differences observed between each spectrum were caused by other factors besides the sample colour. The colour of the plastic samples did not affect spectra obtained from FTIR spectroscopy, but negatively impacted the spectra obtained using Raman spectroscopy.

The labels of the plastic sample also didn’t have much of an impact on the NIR spectra. There was one exception, which was the label of a HDPE bottle that NIR analysis identified to be made from the same material of as a label on a PET bottle. This was the only sample that the NIR analyzer matched to an unexpected sample in the NIR spectral library. Labels impacted the spectra obtained from FTIR spectroscopy, but not the Raman spectra. This meant that both NIR and Raman are not severely impacted by the labels on the samples.

An analysis of plastic samples using a NIR spectral library was also performed. While the correlation was lower than that of the FTIR correlations that were previously performed, the NIR spectral library matched all resin types with the exception of HDPE and LDPE. The NIR instrument couldn't differentiate between the two, which also occurred when the correlations of the plastics were tested with FTIR. The low correlations were likely caused by the library itself. The library created in this project was much smaller than the libraries that could be purchased for plastic identification. These libraries would also contain high-quality spectra as opposed to spectra of varying quality. This could therefore affect the values of the correlations. The correlation percentage of the plastic identification test averaged around 86 %, but the evidence from other studies would suggest that the correlations should be much higher. NIR spectroscopy is a more researched topic for plastic sorting, and it currently has a place in the recycling industry. Therefore, there would be more resources available if the IWMC decided to transform their recycling facilities and methods.

Colour sorting technology was also explored thanks to the help of Dr. Nadja Bressan and her students. Due to the unforeseen circumstances with labour action of the university campus, only a small number of sorting tests could be performed. The code for the sorting apparatus, in theory, would work for any three colour combinations. However, the colour sensor struggled to detect the colour input on the plastic samples due to factors such as the angle of reflection and the shape of the material. Automated colour sorting could be a promising application to implement on PEI, but it would require further testing with adjustments to the sorting apparatus and different colour combinations in order to come to a conclusion.

This project explored NIR spectroscopy and colour sorting on a small scale in order to see how these technologies could be implemented here in PEI. The pros and cons of NIR were weighed against FTIR and Raman spectroscopy, and NIR would be the most beneficial technique to implement. Additionally, there is a physical ease with using NIR spectroscopy due to its “point and click” nature. NIR spectroscopy is not as affected by the labels or colouring of plastics in comparison to other spectroscopic techniques, which makes NIR more advantageous. NIR spectroscopy is also a more accessible option for implementation because there are several manufacturers and products that would be available.

Most plastics in PEI either end up being sent into landfills or a shipped away to other provinces for recycling. By converting PEI’s recycling process into an automated procedure, more recycling could be done within the province. This in turn would also help reduce the number of plastics sent into landfills, which will limit the environmental impact of plastic use in PEI. The improvement of #7 plastics identification and sorting is an area that could be further explored. This project was just one step in the overall goal to improve PEI’s recycling practices, and the conclusions made about NIR spectroscopy and colour sorting help push this goal one step further to reality.

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Appendix A- Sample List

Table A1: Samples included in the NIR spectral library.

Sample Name	RIC #	Sample description
#4	1	Brown vegetable container
#5	4	Gray food container lid.
#7	2	Dove hand soap bottle
#9	1	7-Up bottle
#10	1	Pepsi bottle
#12	6	White plastic dinner plate
#13	6	Plastic office water cooler cup
#14	5	Wendy’s cold drink cup
#16	4	Red squeeze water bottle
#18	5	Wendy’s cup lid

#19	5	Clear food container
#20	6	Tim Hortons hot beverage lid
#21	6	Activia yogurt cup (green label, white cup)
#22	2	Tide Cold water detergent bottle
#23	2	Ivory bodywash
#24	1	Pantene shampoo bottle
#25	5	Blue Tide detergent bottle cap
#27	3	White PVC fragment
#28	4	Bagel bag
#29	3	Brown vinyl flooring.
#31	5	White Pringles cup
#32	5	White food container
#33	6	White Oikos yogurt cup

#34	3	PVC stick
#35	3	PVC white bendy gutter pipe
#36	3	PVC white gutter pipe
#37	5	Clear lid
#38	5	Blue translucent lid
#39	5	Red food container. Translucent.

Table A2: Samples excluded from NIR spectral library.

Sample #	RIC #	Sample description
#1	5	Clear food container lid
#2	5	Black food container
#3	1	Food container lid
#6	5	Cold drink cup
#8	1	Clear plastic box/container
#11	6	Cake container lid
#26	3	Eyeglass cleaner bottle

Appendix B – NIR Spectra

Appendix B can be accessed through the provided Google Drive link.

https://docs.google.com/document/d/1bshZYceNQl3O1ZqUTRVy-law-UIzHhQNzUkyVyrcW_M/edit?usp=sharing