Assessment of the Impact of the Single Stream Recycling on Paper Contamination in Recovery Facilities and Paper Mills

Final Report for REMADE Project: 17-FP-RR-03

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The REMADE Institute Statement

This report documents research that was conducted by University of Miami under a cost-shared subrecipient contract with the REMADE Institute.
The objective of this project is to understand and assess the impact of the single stream recycling on paper contamination in material recovery facilities.
Principal Investigator: Nurcin Celik, University of Miami
REMADE Project Manager: Ed Daniels
The REMADE Institute project number is 17-FP-RR-03 (6.2)

University of Miami Statement

University of Miami conducted cost-shared research to understand and assess the impact of the single stream recycling on paper contamination in material recovery facilities.

The Principal Investigator for the project is: Nurcin Celik, University of Miami

The Project Team included: Haluk Damgacioglu (graduated with Ph.D.), Temitope Runsewe (Ph.D. candidate), Mizelle Hornilla (graduated with B.S.)

Funding for this project was provided by the REMADE Institute with cost-share provided by University of Miami

Our industrial partners are ISRI, AF&PA, and RRS.

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List of Abbreviations

AF&PA	American Forest & Paper Association
ANOVA	Analysis of Variance
ASTM	American Society for Testing and Materials
CR	Contamination Rate
df	Degrees of Freedom
DSR	Dual Stream Recycling
EPA	Environmental Protection Agency
GHG	Greenhouse Gas
HDPE	High Density Polyethylene
ISRI	Institute of Scrap Recycling Industries
MA	Median Age
MHI	Median Household Income
MRF	Material Recovery Facility
MS	Mean Squares
MSR	Multi Stream Recycling
MSW	Municipal Solid Waste
OCC	Old Corrugated Cardboard
ONP	Old Newspapers
PET	Polyethylene Terephthalate
PO	Population
PR	Poverty Rate
REMADE	Reducing EMbodied-energy And Decreasing Emissions
RRS	Resource Recycling Systems
RSE	Relative Standard Error
SS	Sum of Squares
SSR	Single Stream Recycling
VIF	Variance Inflation Factor

Executive Summary

Contaminated recyclables pose one of the largest roadblocks to an effective implementation of a circular economy system. They obstruct the circulation of resources in the system as they need to be discarded. In addition, higher levels of contamination cause material recovery facilities (MRFs) to incur increased processing costs. Current knowledge surrounding the effects of various recycling methods on contamination rates is limited, thus preventing effective quantification of contamination effects. This study aims to fill this knowledge gap by assessing the impact of single stream recycling on paper contamination in MRFs and their end-products based on different composition studies conducted by facilities nationwide.

This project may jointly classify as part of two of REMADE Institute's enabling general technologies: (1) Data collection, standardization, metrics, and tools for understanding material flow, and (5) Rapid gathering, identification, sorting, separation, contaminant removal, reprocessing and disposal of manufacturing materials. The work involves statistical analysis of inbound and outbound contamination samples obtained through material composition studies and investigation of new and emerging methods that promise a substantial reduction of contamination in MRFs. Higher levels of contamination in both the inbound and outbound streams of an MRF may result in (1) higher costs of processing of commingled materials due to additional sorting processes and disposing of the contaminants to the landfills and (2) lower revenues due to fewer accepted samples by paper mills.

This project expects to provide the foundational knowledge that could catalyze significant cost savings and energy consumption at MRFs and paper mills by understanding the levels of inbound and outbound contamination rates in SSR systems. Statistical analysis conducted in this project utilizes the available nationwide inbound and outbound samples collected as part of material composition and audit studies to identify and measure the significance of various factors on the resultant contamination levels. The analysis then synthesizes these results with research performed into emerging contamination reduction techniques to identify ones that have promising effects, making recommendations for future reduction strategies possible. Thus, the study contributes to the knowledge of SSR and its place within a circular economy.

The research results provide benefits to both the recycling industry and its customers by addressing the causes and impact of contamination in recycled products, particularly with the wide applicability of single stream recycling within the United States.

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REMADE Project: 17-FP-RR-03

Introduction

In the United States, there is a steady rise in total solid waste generation. Currently, the total generation of municipal solid waste (MSW) averages 262.4 million tons annually with paper and paperboard comprising its largest percentage (EPA, 2018). Due to the massive amounts of waste produced, effective waste management is of high importance to environmental protection for its potential to incur savings in both cost and greenhouse gas (GHG) emissions, especially as various methods of solid waste management (i.e., recycling, composting, landfilling, and combustion) are involved with energy recovery that contributes to the reusability of the managed resources.

Material recovery facilities (MRFs) serve as a gross sorting and limited processing point for recycled materials, after which materials are then transferred to the consumers of recycled materials for further processing. Various challenges are faced by the quality and quantity of recyclable materials during processing at the MRFs. When recyclable materials are compromised or contaminated, the recovery rate of recyclables drops or could even render the recyclables totally useless (Bohlig, 2013). A major factor that could contribute to the contamination rate of recyclable materials are the embedded recyclables collection programs. The three major recyclables collection methods available in the U.S. are single stream recycling (SSR), dual stream recycling (DSR) and multi stream recycling (MSR). A single stream (or commingled) refers to when recyclables of different kinds (i.e., glass, bottles, paper or metals) are collected in a single container, while a dual stream consists of two containers with one specifically used for the collection of paper fiber products (i.e., paper and cardboards). In multi stream, material generators are required to sort recyclables in two or more separate containers, typically having a container distinctly for paper fiber products, plastics, and aluminum and other recyclables (Lakhan, 2015).

Amongst the curbside recycling programs, single stream recycling has grown rapidly during the past decade due to (i) its ability to use automated collection services thereby improving safety (SSI, 2020) (ii) its capabilities to better attract the participation of communities in recycling while reducing the cost of collecting curbside recyclables and avoiding a cumbersome sorting process at the individual level (Farrell 2003; HDR 2012). However, SSR systems operate at the expense of facing significant technical and economic barriers in terms of higher contamination in collected materials, higher volumes of materials requiring pre-sorting at regional MRFs, highly contaminated recyclable materials directed to the mills, and reliance on export markets (AF&PA, 2004; Berenyi, 2007; Yasar et al., 2017). An increase in contamination may translate to an increase in sorting and separation, a reduction in quality of recycled material and an increase in the total processing cost of recyclable materials.

This project aims to contribute to fill the gap in our knowledge on understanding the impact of SSR on paper contamination in recovery operations by (i) identifying to what extent the recovered fiber is contaminated, (ii) evaluating if SSR has a significant role in the paper contamination, and (iii) exploring emerging recovery processes to prevent from fiber contamination.

Project Objectives and Benefits

Higher contamination levels create technical and economic barriers for processing and treating collected materials cost-effectively (to result in high-quality recyclables) (Janetsky, 2018; Margolis, 2018). Yet, there is a lack of knowledge in the literature in terms of the quantified impact of SSR collection on paper contamination. This REMADE foundational project has been conducted to identify the factors that contribute to contaminating inbound and outbound recyclable materials to and from MRFs designed for single stream recyclable processing. These factors may be the collection modes or strategies, region specific variables (e.g., household participation rates in curbside collection), input volumes, or technology. In this study the systematic investment or related initiatives in education and promotion of curbside recycling collection programs was not considered. Collection strategies include municipal guidelines that dictate what may or may not be inside of the curbside recycle bin. The project is also aimed at identifying and analyzing emerging technologies or practices that can reduce inbound and outbound contamination rates of recycled products and hence enable higher recycling rates for materials. This work assumes recyclable inbound to a MRF as the same as outbound to the collection system and adopts "MRF inbound and outbound" for consistency purposes.

This project utilizes various technical information and resources (e.g., MRF input capacity, and processing technologies for recovery/separation of recyclables) to identify key factors that may affect variations in SSR contamination rates (e.g., capacity, collection strategies, processing practices and technology). In summary, the project objectives are:

- Objective 1. Investigate the impact of SSR collection strategies and processing technologies on paper contamination in MRFs at multi-regional levels relative to alternative collection modes such as DSR and MSR systems and determine to what degree the fiber contamination rates apply nationally using secondary samples (prior composition and audit studies).
- Objective 2. Develop recommendations for best practices according to identified factors that appear to yield minimal contamination rates of paper recyclables (e.g., SSR collection strategy, type of inbound materials, collection source such as single and multi-family residential and commercial, participation rates, and other factors).
- Objective 3. Identify new and promising practices and technologies for contamination control in SSR systems.

Project Approach

This project proves relevant to various industries in recycling and solid waste management such as recyclables collection, material sorting and processing, and paper recovery by aiming to discover the significant causes of paper contamination at MRFs. This project may jointly classify as part of two of REMADE Institute's enabling general technologies: (1) Data collection, standardization, metrics, and tools for understanding material flow , and (5) Rapid gathering, identification, sorting, separation, contaminant removal, reprocessing and disposal, and presents a foundational study example for connecting the nodes of Systems Analysis and Integration to Recycling and Recovery, by collecting information that drives industrial decision making, and investigating methods and programs that apply to the waste management industry (e.g., waste collection, and pulp recycling for reduced contamination rates).

Task 1. Collection of recyclables composition data for recovered materials in MRFs. Collecting contamination data within different collection systems and different MRFs involves reviewing documented material including waste composition studies and audits, composition reports, summaries, direct observation when visiting sites, and interviewing (in-person, e-mail, or phone conversations). Data is then standardized before the statistical analysis for consistency purposes (to the extent possible) as each study may provide individual sample results via material-by-material breakdowns of recyclables. Contamination is investigated in old corrugated containers and old newsprint types of paper based on weight percentages of prohibitive materials and out-throws (browns) in the sample bale.

Task 2. Collection of data via on-site sampling and data analysis. On-site sampling has not been performed in this study as the collected sample data from waste composition reports was sufficient to develop a confident statistical assessment. A sufficient inbound and outbound contamination data for developing a confident statistical assessment was determined based on the industry-accepted standards for statistical sampling provided by the American Society for Testing and Materials (ASTM, 2016)

Task 3. Assessment of new and promising collection and sorting methods to decrease contamination in MRFs. This task is where additional or alternative sorting practices such as collecting glass on the curb, limited compaction of recyclables in collection trucks, and employment of more efficient sorting methods and technologies for separating materials are investigated. Different statistical tests (i.e., multi-variate ANOVA, t-testing etc.) are used at different confidence levels to compare contamination and recycling rates, and costs of different technologies used in SSR, DSR, and MSR facilities. The preliminary cost-benefit analysis conducted at the last stage of this project is aimed to aid the adoption of new, emerging recycling programs that minimize contamination by identifying region-specific factors. These region-specific factors are recycling and residual rates, current and planned recycling systems, costs, required operational expertise and equipment, and implementation feasibility. We conduct the analysis based on:

- New technologies that are being used in MRFs that offer promising results on reducing paper contamination,
- State of the art patents that are not currently implemented, but can decrease contamination in MRFs,
- Improved techniques of curbside collection that eliminates fiber material contamination in the source.

Our cost-share industry partners included: 1) Resource Recycling Systems (RRS), 2) the American Forest and Paper Association (AF&PA) and 3) the Institute of Scrap Recycling Industries (ISRI). These three partners provided their expertise and guidance in each task of the project, in particular in defining the type of samples to be collected and help collect data from their respective organizations in Task 1, in assisting UM team in the interpretation of the results from the data analysis in Task 2, and in providing their inputs and perspectives related to emerging technologies and practices to enable further contaminant reduction in paper from SSR in Task 3.

Project Accomplishments

The accomplishments of this project maps directly to the goals and objectives of the outlined tasks. The first accomplishment is the successful collection of sufficient inbound and outbound paper contamination sample data from MRFs in the considered regions. The sample sizes and numbers required for each of the regions and each of the contamination forms (inbound and outbound) are calculated to establish a confidence interval of 95% based on ASTM standards (ASTM, 2016). Achieving this standard required extensive communication with project sponsors and external MRFs.

The second accomplishment of this project is the identification of the differences between various recycling methods and the key factors that influenced contamination rates. This task is accomplished by applying the statistical methods outlined earlier to the four nationwide regions.

Project Results

Task 1. Collect data from MRFs operating under different collection modes and strategies

Task 1. Objective

The objective of this task is to collect and standardize the data from MRFs that enables a valid statistical analysis and identification of the factors that influence contamination rates in recovered and recycled paper for SSR, DSR and MSR MRFs. Within the sample data, the following information is noted: 1) region, 2) MRF capacity (inbound volume) or the amount of waste/recyclables generated, 3) collection mode (e.g., single stream, dual stream, multi stream), 4) SSR collection strategy (e.g., SSR excluding glass, SSR excluding glass and plastic films, SSR excluding foamed plastics), 5) collection sources (e.g., single-family, multi-family, commercial, etc.), 6) products recovered for recycling (the amount/percentage composition of material recycled by commodity), 7) inbound and outbound contamination (type and concentration), 8) Date/year of the data collected and 9) studies of the population served by the MRF. Information related to products recovered for recycling was collected and used in the inbound analysis as composition reports also contain contamination data. Information related to participation rates of the population served was additionally collected in the South region, and not used in the analysis of other regions due to the lack of sufficient data.

Task 1. Results

For statistical analysis conducted in this work, the U.S. is divided into four major regions based on the sample availability and proximity as the following, noting that results may change if granularity of this division is changed.

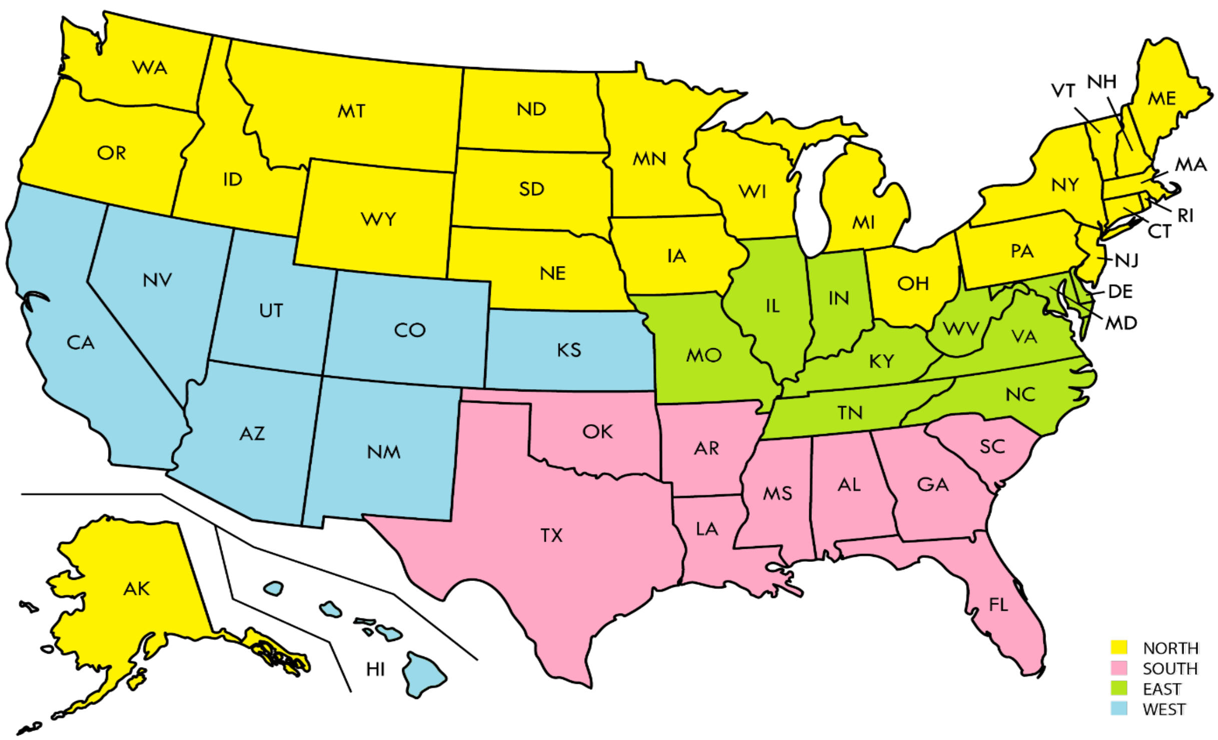

Figure 1. Division of states into regions

The sample size requirements for different contamination analysis sets are determined as shown in Table 1 based on the ASTM Standard d5231-92(2008) with a 95% confidence level (ASTM, 2016).

Table 1. Inbound and outbound data point requirements for different regions

Region	Inbound - sample size required	Inbound - sample size available	Outbound- sample size required	Outbound - sample size available
East	34	85	30	47
West	34	174	30	84
North	34	285	30	158
South	34	215	30	85
Total	136	759	120	374

Task 2.0. Analyze and interpret the data to quantify differences in contamination rates and to identify key factors impacting contaminations rates

Task 2.0. Objective

The objectives of this task are 1) to conduct a rigorous statistical analysis of the available sample data to quantify differences in inbound and outbound contamination rates within and across regions for various collection modes (e.g., SSR, DSR and/or MSR depending on data availability), and 2) to identify and interpret those key factors that appear to influence contamination through data observation and statistical analysis.

Task 2.0. Results

The composition data for recovered materials, inbound and outbound contamination data, and the contamination incident data for recovered materials in material recovery facilities have presented challenges pertaining to sample consistency and availability. While some states require county governments, state agencies, and state supported colleges to report the amount and type of materials recycled (CLI, 2018), other businesses and recycling industries are encouraged but not required to report their recycling activities (FDEP, 2018). To address this challenge, the sample data collected were first cleansed and standardized to remove specific organization information and create a more consistent pooled database.

2.1 Inbound Contamination: South Region

Descriptive statistics of both SSR and DSR contamination rates are shown in Table 2 for the South region. The mean and standard deviation of paper contamination rate in SSR (percent of total contamination) are found to be 18.54 and 8.97, respectively, both of which are higher than those of DSR contamination rates (i.e., 3.89 and 3.08, respectively).

Table 2. Descriptive analysis for DSR and SSR

	N	CR Mean	Std. Deviation	Std. Error	95% Confidence Interval for the Mean		Min	Max
					Lower Bound	Upper Bound		
DSR	45	3.898	3.084	0.460	2.972	4.825	0.570	13.500
SSR	170	18.541	8.973	0.688	17.183	19.899	1.760	48.200
Total	215	15.476	10.060	0.686	14.124	16.829	0.570	48.200

Figure 2 shows the boxplot of samples for DSR and SSR along with their outliers. The variance of SSR sample is higher than that of DSR suggesting that the rates within the SSR sample are spread over a wider range in comparison to that of the DSR sample. The two box plots also reveal a recognizable difference in terms of samples' plotted height, median, and distribution. Any evident difference between two groups is worthy of additional analysis of data.

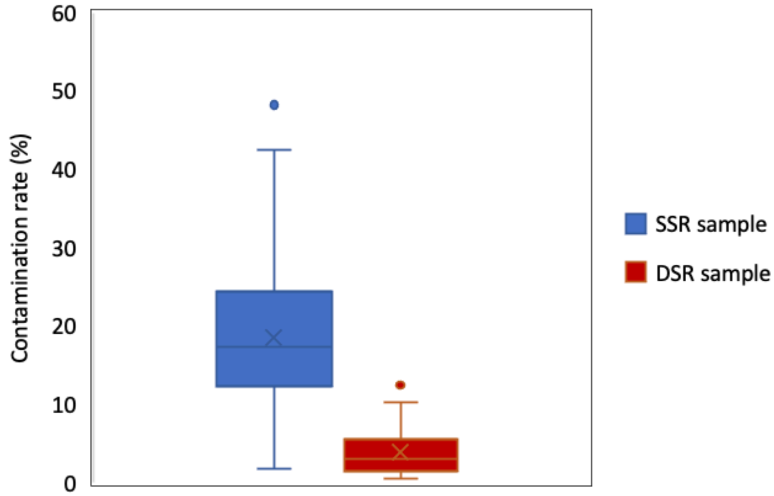

Figure 2. Boxplots of SSR and DSR samples, South region

The difference between the two sample groups is further investigated via analysis of variance (ANOVA) and t-tests. 90 samples are used in the single factor ANOVA with SSR and DSR samples each having 45 data points. The ANOVA expressions in Table 3 compare the ratio of "between group variance" to "within group variance" and the "F critical ratio". Between group variation and within group variation are donated by SS_B and SS_W, respectively. SS_T is the sum of SS_B and SS_W. K is the number of groups and N is the number of observations at each level.

Table 3. ANOVA expression table: South region

Source of Variation	*SS*	*df*	*MS*	*F*
Between Groups	SS_B	K-1	$MS_B = SS_B$ / (K-1)	MS_B / MS_W
Within Groups	SS_W	*N-K*	$MS_W = SS_W$ / (N-K)	
Total	SS_T	*N-1*		

In Table 4, the factor (independent variable) is the type of recycling program, the levels are SSR and DSR, and the dependent variable is contamination rates across various MRFs that implement different recycling programs. The number of observations at different levels are not equal (12 MRFs are observed for SSR and 4 MRFs are observed for DSR). The tested null hypothesis (H_0) is "having equal contamination rates in SSR and DSR" while the alternative hypothesis (H_1) is "Not". The ANOVA F-test evaluates if the means of different levels on the dependent variable are significantly different from each other. If the calculated F ratio is smaller than "F critical ratio", the null hypothesis cannot be rejected. Otherwise, the null hypothesis is rejected where the contamination rates of SSR and DSR are found to be significantly different than each other. In this work, ANOVA was performed using Microsoft Excel Data Analysis Tool and the results are shown in Table 4.

Table 4. ANOVA of inbound contamination samples in South region

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Groups	10785.53	1	10785.53	279.966	4.45E-29	3.949
Within Groups	3390.157	88	38.52451			

Total	14175.69	89

As the $p - value$ is less than 0.05, we reject the null hypothesis and conclude that there is a significant difference between the mean contamination rates of SSR and DSR.

2.2 Linear Regression Model on Inbound Contamination: South Region

In establishing a linear regression model, the response variable is selected as the total contamination rate (CR) where the explanatory variables are median age (MA), median household income (MHI), poverty rate (PR), and population size (PO). Because the response variable does not follow a normal distribution, a square root (sqrt) transformation is used to transform the data. The correlation matrix of numerical variables is shown in Figure 3.

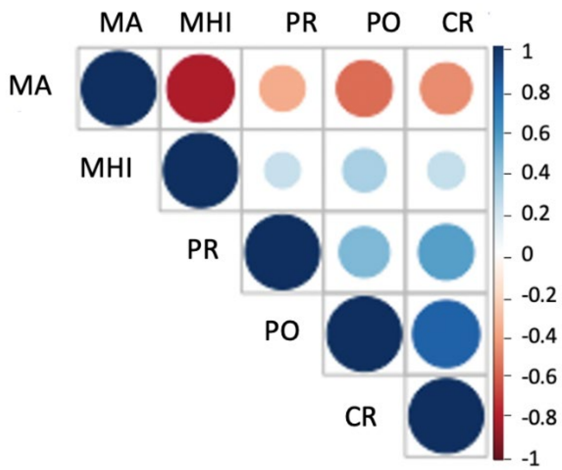

Figure 3. Correlation matrix of numerical variables

A multiple linear regression was performed with contamination rate being the response variable. Model diagnostics were performed to test and examine adherence to assumptions of (1) linearity, (2) independent, normally distributed residuals with constant variance (homoscedasticity), (3) linearly independent predictors (absence of collinearity), and (4) exertion of equal influence by all observations. Backward and forward stepwise regression was performed. Because multicollinearity is found to exist in the model, the factor with the highest variance inflation factor (VIF) (in this case median age) was removed and a stepwise selection model using backward direction is used. The final model is provided in Table 5.

Table 5. Summary of multiple linear regression of inbound stream sample set in South region

Residuals:				
Min	1Q	Median	3Q	Max
-0.215	-0.066	-0.006	0.062.	0.265

Coefficients:				
	Estimate	Std. Error	t-value	P-value
(Intercept)	-1.657e-01	6.994e-02	-2.369	0.019
MHI	2.853e-06	1.190e-06	2.397	0.016
PO	1.246e-07	8.830e-09	14.111	< 2e-16
PR	1.826e+00	2.858e-01	6.390	1.2e-09

Median household income, population and poverty rate are found to be the major contributors to increasing contamination. The model has an adjusted *R*-squared value of 0.7015 after implementing a stepwise selection with a residual standard error (RSE) value of 0.0948 which shows that a linear relationship exists between the considered predictor variables and the response variable. VIF was used to check for the multicollinearity where no multicollinearity is found to exist in the resultant model.

2.3 Outbound Contamination: South Region

From the 35 OCC samples compiled, the average rate of acceptable recovered material was found to be 91.12% while the same rate was 67.41% when calculated from the 266 ONP samples. Other materials such as brown paper, out-throws and prohibitive items are assessed in Figures 4 and 5.

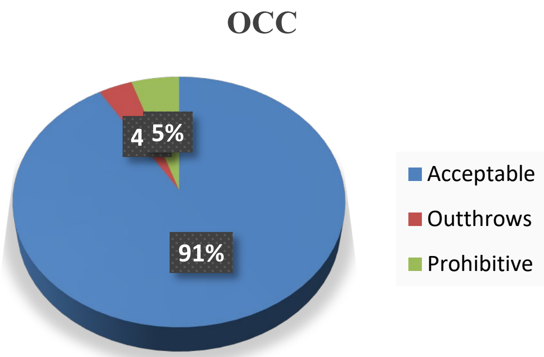

Figure 4. Composition of contamination types in OCC

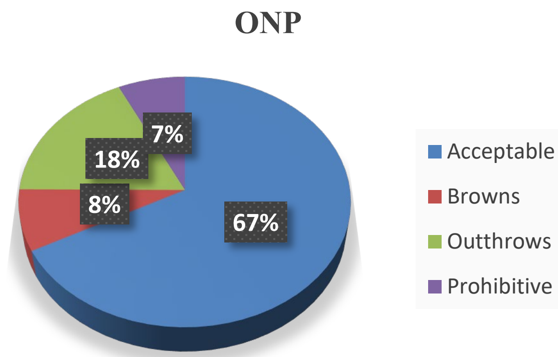

Figure 5.Composition of contamination types in ONP

Different types of contamination including brown paper, prohibitive items, and other outthrow materials were analyzed from the OCC and ONP samples. Figure 4 shows the outthrow and prohibitive rates for 35 samples from the OCC stream and Figure 5 shows brown paper, outthrow, and prohibitive rates from 50 samples of ONP. Figures 6 to 12 show the rates of outthrows, prohibitive materials, browns and total outbound contamination in both OCC and ONP material streams. From the figures below, the mean contamination rate is higher than the maximum acceptable limit by China (ISRI, 2013) in both OCC and ONP streams.

<u>OCC material stream</u>

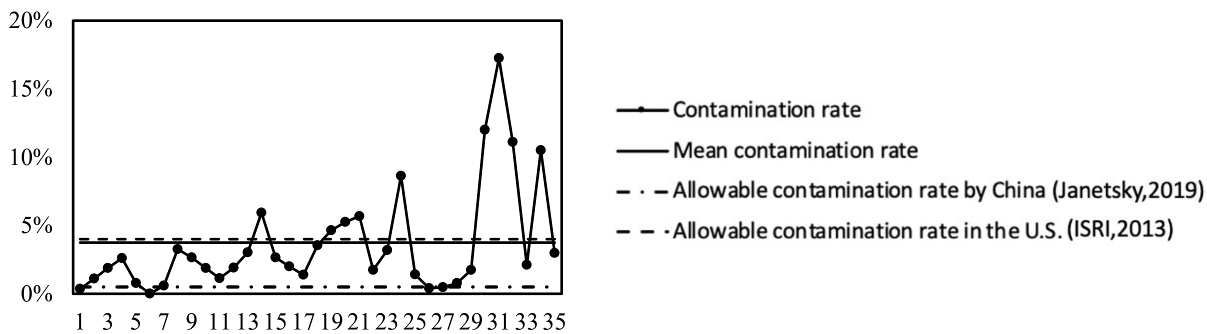

Figure 6. Outthrows in OCC

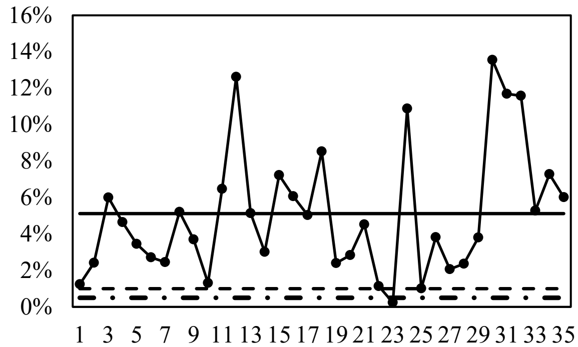

Figure 7. Prohibitive materials in OCC

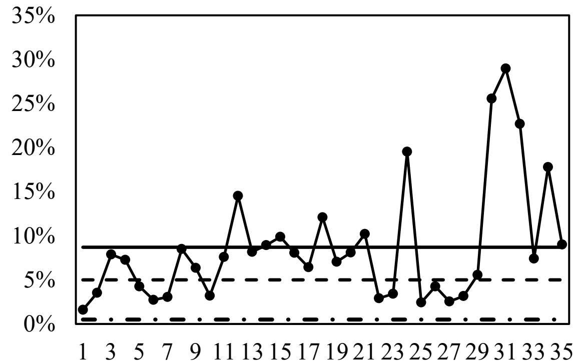

Figure 8. Total contamination in OCC

<u>ONP Material stream</u>

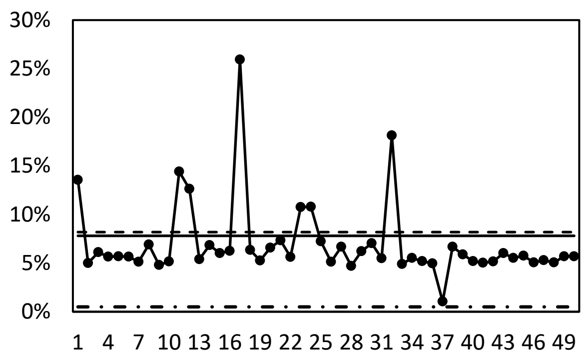

Figure 9. Browns in ONP

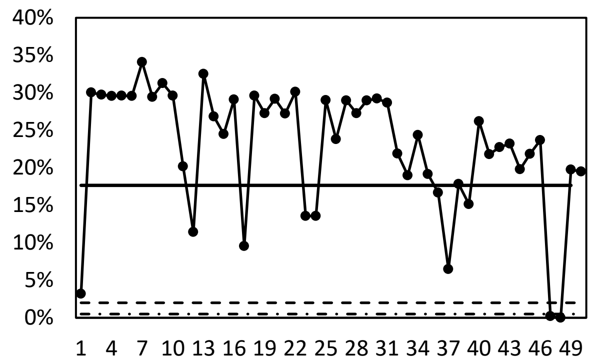

Figure 10. Outthrows in ONP

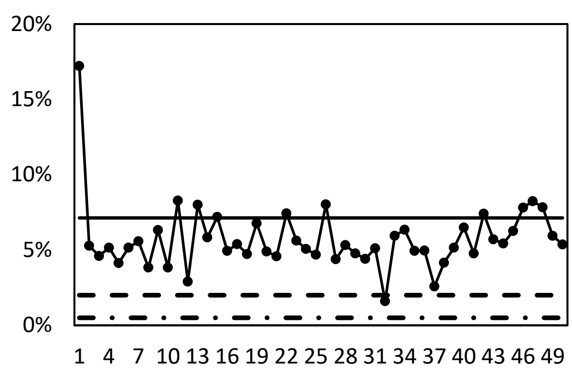

Figure 11. Prohibitive materials in ONP

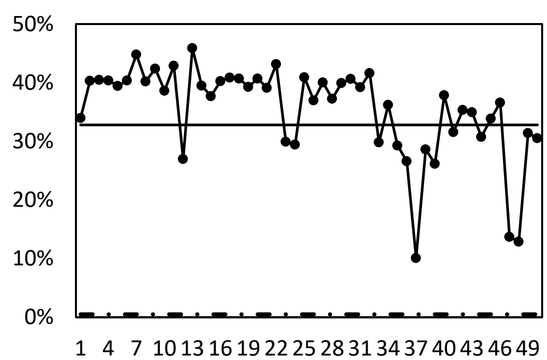

Figure 12. Total contamination in ONP

The mean and standard deviation of the ONP outthrow sample set are found to be 17.77 and 6.84 respectively, both of which are higher than mean and standard deviation and of the OCC outthrow sample set which are 3.62 and 3.89, respectively.

2.4 Inbound Contamination: North Region

Descriptive statistics of both SSR and DSR contamination rates are shown in Table 2 for the North region. The mean and standard deviation of paper contamination rate in SSR (percent of total contamination) are found to be 3.59 and 3.16, respectively, both of which are slightly higher than those of DSR contamination rates (i.e., 2.20 and 1.67, respectively).

Table 6. Descriptive analysis for DSR and SSR, North region

	N	CR Mean	Std. Deviation	Std. Error	95% Confidence Interval for Mean		Min	Max
					Lower Bound	Upper Bound		
DSR	49	0.109	0.069	0.010	0.089	0.129	0.020	0.284
SSR	236	0.259	0.140	0.009	0.241	0.277	0.000	0.717
Total	285	0.233	0.142	0.008	0.217	0.250	0.000	0.717

ANOVA test is performed between DSR and SSR programs in the North region to determine whether there is a statistically significant difference between the CR means of DSR and SSR programs. SSR and DSR samples used in this test were consisted of 239 and 49 observations, respectively. Figure 13 shows the boxplot of samples for DSR and SSR along with their outliers.

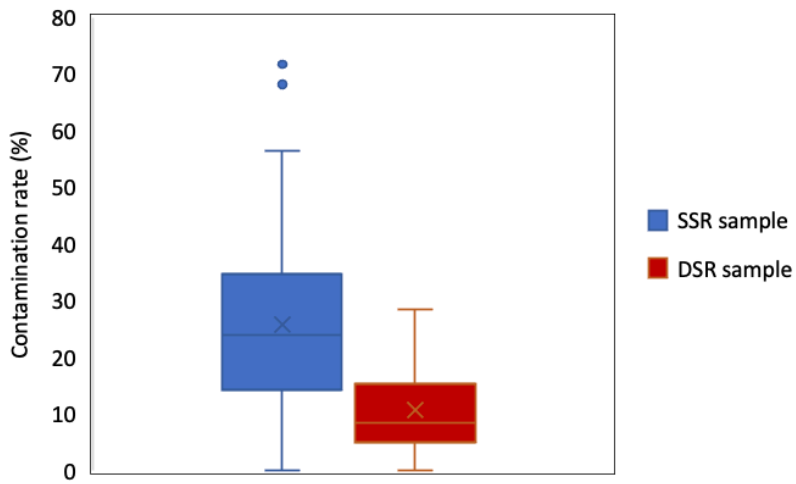

Figure 13. Boxplots of SSR and DSR samples, North region

The tested null hypothesis (H_0) is "having equal contamination rates in SSR and DSR" while the alternative hypothesis (H_1) is "Not". The ANOVA F-test evaluates if the means of different levels on the dependent variable are significantly different from each other. In this work, ANOVA was performed using Microsoft Excel Data Analysis Tool and the results are shown in Table 7. As the $p-value$ for the ANOVA test (3.16E-12) is significant at alpha 0.05 level, we rejected the null hypothesis test at a 95% confidence level and concluded that there is a significant difference between the mean contamination rates of SSR and DSR.

Table 7. ANOVA of inbound contamination samples in North region

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Groups	0.909	1	0.909	53.110	3.16E-12	3.875
Within Groups	4.843	283	0.017			
Total	5.752	284				

2.5 ANOVA on Inbound Contamination across SSR Facilities: North region

One-way ANOVA was performed across the considered facilities accepting recyclables from SSR programs in the North region to determine if the mean contamination rates in the inbound streams are equal across the four facilities observed. Table 8 shows the descriptive analysis for different facilities accepting recyclables from SSR programs in the North region.

Table 8. Descriptive analysis of contamination rate for facilities accepting recyclables from SSR programs in North region

	N	CR Mean	Std. Deviation	Std. Error	95% Confidence Interval for Mean		Min	Max
					Lower Bound	Upper Bound		
Facility 1	176	0.185	0.086	0.007	0.172	0.198	0.000	0.420
Facility 2	35	0.158	0.082	0.014	0.130	0.187	0.000	0.300
Facility 3	14	0.145	0.037	0.010	0.124	0.166	0.080	0.200
Facility 4	31	0.190	0.114	0.021	0.148	0.231	0.000	0.470
Total	256	0.180	0.088	0.006	0.169	0.190	0.000	0.470

A total of 256 observations from all four facilities are used in the descriptive analysis with its corresponding break down shown in Table 8. The highest mean contamination rate was 18.95% in Facility 4, while the lowest mean contamination rate is 14.47% in Facility 3. However, the highest standard deviation was in Facility 4. Figure 14 also shows the boxplots of the samples from different facilities accepting recyclables from SSR programs in the North region.

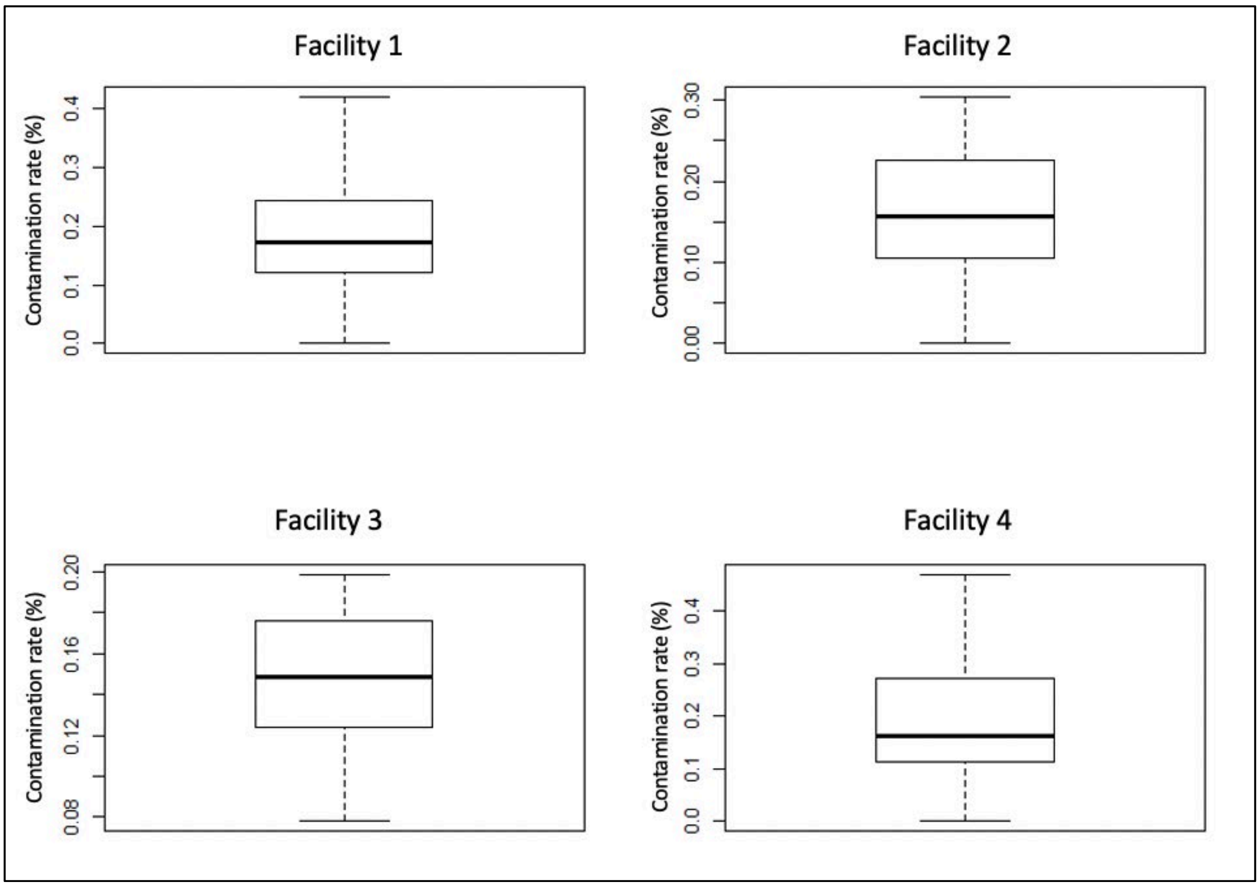

Figure 14. Boxplots for contamination rates in different facilities in North region

Kolmogorov-Smirnov normality test with alpha = 0.01 was used to test the normality of the four group of samples with the null hypothesis (H_0) being "the available sample data follows a normal distribution" versus the alternative hypothesis (H_1) of "Not". The $p - value$ of the conducted Kolmogorov-Smirnov normality test for the facilities 1, 2, 3 and 4 were 0.0215, 0.4153, 0.7293 and 0.1295, respectively. Thus, we fail to reject the null hypotheses for the Kolmogorov-Smirnov normality tests and concluded that the sample data follows a normal distribution.

Table 9. ANOVA of inbound contamination samples in North region

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*
Between Groups	0.040	3	0.013	1.756	0.156
Within Groups	1.933	252	0.008		
Total	1.973	255			

In Table 9, the tested null hypothesis (H_0) is "having equal contamination rates across SSR facilities" while the alternative hypothesis (H_1) is "Not". The ANOVA F-test evaluates if the means between two populations are significantly different from each other. The result shows that the $p-value$ is not significant at an alpha value of 0.05. Therefore, we fail to reject the null hypothesis and conclude that there is no statistically significant evidence that shows the mean contamination rates in the inbound streams across the considered facilities in the North region are different from each other.

2.6 Linear Regression Model on Inbound Contamination: North Region

In the developed linear regression model, the response variable is selected as the total contamination rate where the categorical explanatory variables are median household income, median age, population size and poverty rate. Because the response variable does not follow a normal distribution, a square root (sqrt) transformation is used to transform the data. The correlation matrix of numerical variables is shown in Figure 15 where MHI is the median household income, MA is the median age, PO is the population, PR is the poverty rate and CR is the contamination rate.

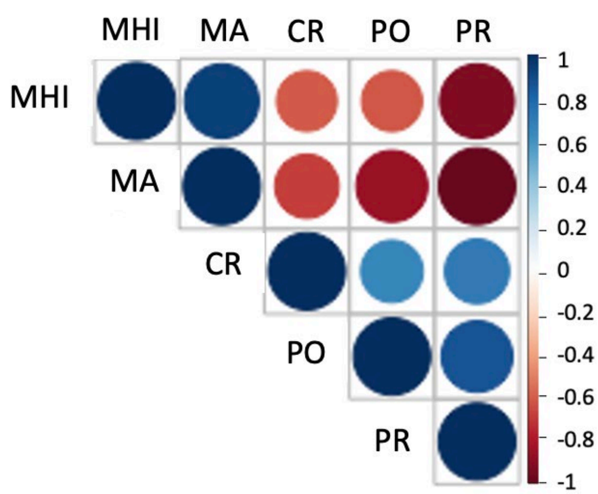

Figure 15. Correlation matrix of numerical variables

A multiple linear regression was performed with contamination rate being the response variable. Model diagnostics were performed to test and examine adherence to assumptions of (1) linearity, (2) independent, normally distributed residuals with constant variance (homoscedasticity), (3) linearly independent predictors (absence of collinearity), and (4) exertion of equal influence by all observations. Backward and forward stepwise regression was performed. VIF was used to detect multicollinearity and no multicollinearity is found to exist in the model. The final model is provided in Table 5, where median household income, population and poverty rate are found to be the major contributors to increasing contamination with an adjusted R-squared value of 0.5073 and a RSE value of 0.0876.

Table 10. Summary of multiple linear regression of inbound stream sample set in North region

Residuals:				
Min	1Q	Median	3Q	Max
-0.188	-0.064	-0.002	0.060	0.224

Coefficients:

	Estimate	Std. Error	t-value	P-value
(Intercept)	-2.078e-01	2.206e-01	-0.942	0.348
MHI	4.231e-06	2.847e-06	1.486	0.140
PO	1.246e-07	8.830e-09	14.111	< 2e-16
PR	2.428e+00	4.469e-01	5.431	3.2e-07

2.7 Outbound Contamination: North Region

The contamination rates and event occurrences in the outbound contamination incident data of multiple facilities in the North region between 2015-2019 were plotted for different waste streams in Figures 16-19.

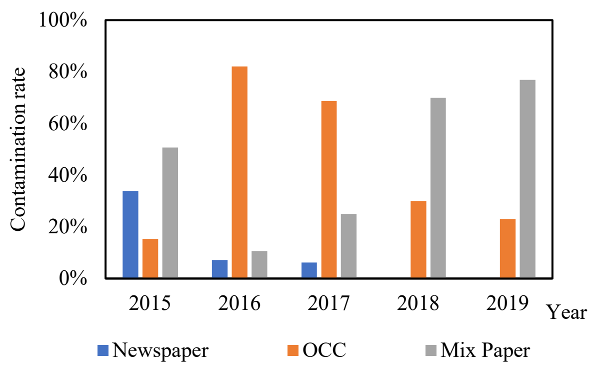

Figure 16. Contamination rate in different material streams between 2015-2019

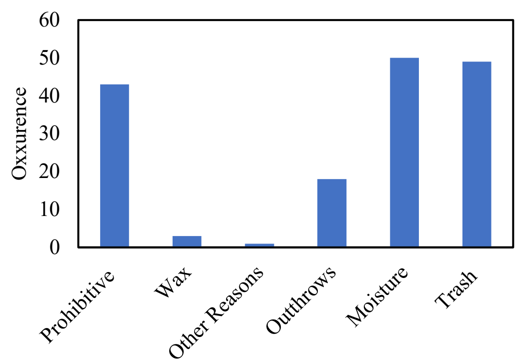

Figure 17. Contamination incidents in mixed paper bales between 2015-2019

From the contamination incident data collected in all facilities, mixed paper is found to have the highest contamination followed by newspaper and then OCC, HDPE, PET and steel cans. Next, the major contributors to the contamination in the mixed paper, newspaper, and OCC stream are studied. Figures 18 and 19 show that the major incidents in the mixed paper bales are moisture, trash contamination, and prohibitive materials whereas in the newspaper stream, the major incidents are found to be moisture, outthrows, and prohibitive materials. In the OCC bales, the major incidents are noted as the presence of wax, outthrows, and prohibitive materials.

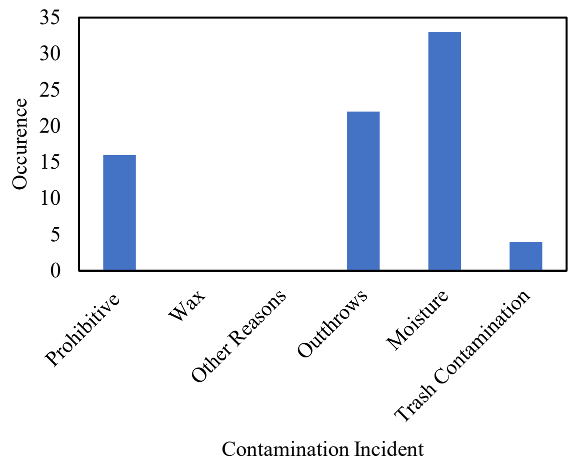

Figure 18. Contamination incidents in newspaper bales between 2015-2019

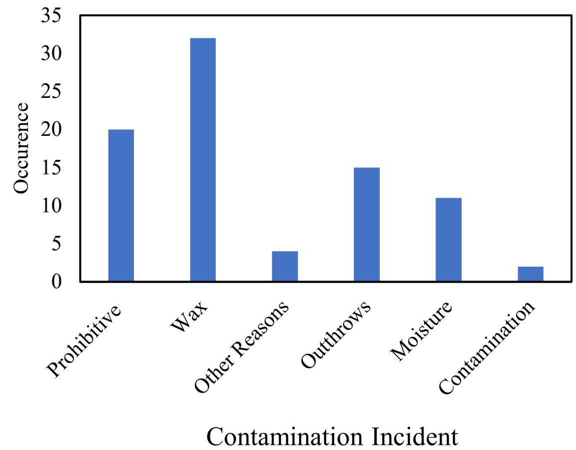

Figure 19. Contamination incidents in OCC bales between 2015-2019

2.8 Inbound Contamination and the Linear Regression Model: East Region

This section describes the analysis of inbound and outbound contamination rates in the East region. We investigate the significant factors that contribute to increasing the contamination level in the inbound stream. The considered sample data was consisted of independent samples of SSR materials from different facilities in the East region. Similar to previous analyses on the South and North regions, a multiple linear regression was fit to the data with the response variable being the total contamination rate and the categorical explanatory variables being median household income, median age, population size and poverty rate. The mean and standard deviation of paper contamination rate in SSR (percent of total contamination) are found to be 17.57 and 1.06, respectively. The correlation matrix of numerical variables is shown in Figure 20.

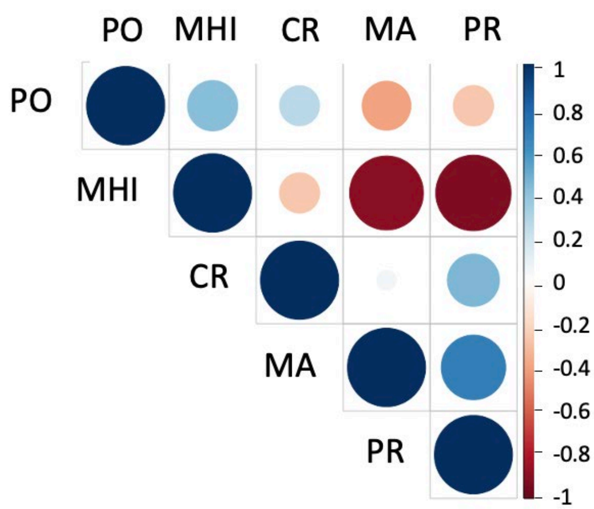

Figure 20. Correlation matrix of numerical variables in the East region

Model diagnostics were performed to test and examine adherence to assumptions of (1) linearity, (2) independent, normally distributed residuals with constant variance (homoscedasticity), (3) linearly independent predictors (absence of collinearity), and (4) exertion of equal influence by all observations. Backward and forward stepwise regression was performed. VIF was used to detect multicollinearity and no multicollinearity is found to exist in the model. The final model is provided in Table 11, where median household income, poverty rate and population are found to be the major contributors to increasing contamination with an RSE value of 0.0849. VIF was used to detect multicollinearity and no multicollinearity exists in the model.

Table 11. Summary of multiple linear regression of inbound stream sample in East region

Residuals:

Min	1Q	Median	3Q	Max
-0.172	-0.058	-0.001	0.050	0.237

Coefficients:

	Estimate	Std. Error	t-value	P-value
(Intercept)	-1.387e-01	1.366e-01	-1.015	0.313
MHI	2.270e-06	9.074e-07	2.502	0.014
PR	2.419e-02	5.249e-03	4.609	1.51e-05
PO	1.354e-07	4.954e-08	2.733	0.008

2.9 Outbound Contamination: East Region

A descriptive analysis of the outbound contamination sample data of multiple facilities are displayed in Table 12 for the East region. A one-way ANOVA was performed to determine whether there are statistically significant differences between the contamination rate means in all facilities. Facilities 1, 3, and 4, each consists of 9,16 and 17 observations respectively whereas Facility 2 consists of just 2 observations. Due to the small sample size, facility 2 was excluded from the ANOVA presented in Table 13. ANOVA was performed using Microsoft Excel Data Analysis Tool and the results are shown in Table 13.

Table 12. Descriptive analysis of contamination rates by facility in the East region

	N	CR Mean	Std. Deviation	Std. Error	95% Confidence Interval for Mean		Min	Max
					Lower Bound	Upper Bound		
Facility 1	9	0.064	0.026	0.007	0.037	0.065	0.009	0.114
Facility 3	16	0.021	0.018	0.005	0.011	0.031	0.001	0.059
Facility 4	17	0.057	0.022	0.005	0.046	0.068	0.008	0.114

Table 13. ANOVA of outbound contamination by facility in the East region

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Groups	0.015	2	0.008	17.859	3.119E-06	3.238
Within Groups	0.017	39	0.0004			
Total	0.032	41				

In Table 13, the tested null hypothesis (H_0) is "having equal contamination rates across all facilities" while the alternative hypothesis (H_1) is "Not". The result shows that the $p - value$ of the hypothesis is less than 0.05. Therefore, we reject the null hypothesis and conclude that there is a statistically significant difference between the mean contamination rates in these facilities. Despite having a small sample in facility 2, the results including facility 2 remains consistent with when it is excluded.

Figure 21 shows the prohibitive rates (measuring the amount of prohibitive excluding other contamination types such as outhrows and browns)) for all samples from the mixed paper stream against the paper mill allowable limits, where solid dot lines, solid lines, dash dot lines, and dash lines demonstrate the contamination rate, mean contamination rate, maximum allowable contamination rate by China, and maximum allowable contamination rate in the U.S. respectively. The mean contamination rates are shown to be higher than the maximum allowable limits by China. Also, contamination rates of majority of samples appear to be above the dash and dash dot lines, making them exceed the allowable limits provided by the paper mills in the U.S. (ISRI, 2013) and China (Janetsky, 2018). Figure 21 shows that at the individual level, 12.5% and 27.1% of the available samples pass the allowable contamination limits by China and U.S. paper mills.

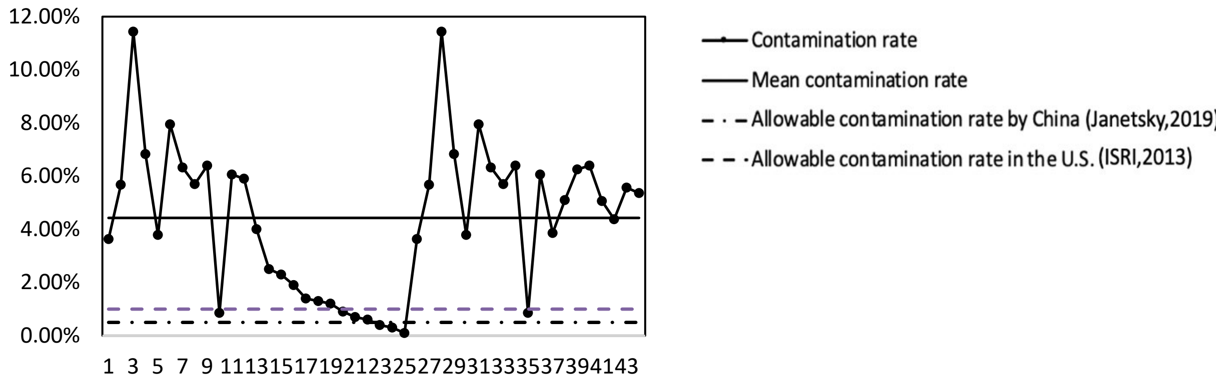

Figure 21. Prohibitive contamination analysis in mixed paper bales

2.10 ANOVA on Inbound Contamination across SSR Facilities: West Region

In this section, one-way ANOVA was performed across the considered facilities accepting recyclables from SSR programs in the West region to determine if the mean contamination rates in the inbound streams are equal across the facilities observed. Kolmogorov-Smirnov normality test was used to test the normality of the group of samples with the null hypothesis (H_0) being "the available sample data follows a normal distribution" versus the alternative hypothesis (H_1) of "Not". Because the sample does not follow a normal distribution, a square root (sqrt) transformation is used to transform the data. ANOVA was performed using Microsoft Excel Data Analysis Tool and the results are shown in Table 14.

Table 14. ANOVA table SSR across facilities for West region

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Groups	0.093	6	0.016	7.110	0.00	2.152
Within Groups	0.367	168	0.002			
Total	0.461	174				

In Table 14, the tested null hypothesis (H_0) is "having equal contamination rates across SSR facilities" while the alternative hypothesis (H_1) is "Not". The result shows that the $p - value$ of the hypothesis is less than 0.05. Therefore, we reject the null hypothesis and conclude that there is a statistically significant difference between the mean contamination rates in these facilities.

2.11 Linear Regression Model on Inbound Contamination: West Region

This section describes the analysis of inbound and outbound contamination rates in the West region. We investigate the significant factors that contribute to increasing the contamination level in the inbound stream. The considered sample data was consisted of independent samples of SSR materials from different facilities in the West region. Similar to previous analyses on other regions, a multiple linear regression was fit to the data with the response variable being the total contamination rate and the categorical explanatory variables being median household income, median age, population size and poverty rate. The mean and standard deviation of paper contamination rate in SSR (percent of total contamination) are found to be 11.01 and 1.18, respectively. The correlation matrix of numerical variables is shown in Figure 22.

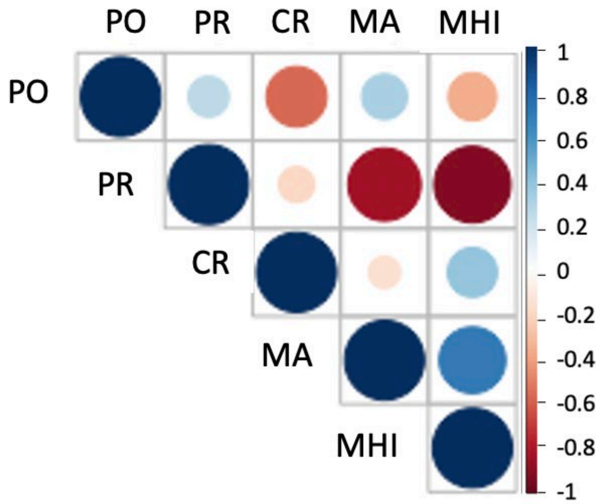

Figure 22. Correlation matrix for numerical variables in the West region

Model diagnostics were performed to test and examine adherence to assumptions of (1) linearity, (2) independent, normally distributed residuals with constant variance (homoscedasticity), (3) linearly independent predictors (absence of collinearity), and (4) exertion of equal influence by all observations. Backward and forward stepwise regression was performed. VIF was used to detect multicollinearity as a result of which a variable is removed from the model. The final model is provided in Table 15, where median household income, median age and population are found to be the major contributors to increasing contamination with an RSE value of 0.0791. VIF was used to detect multicollinearity and no multicollinearity exists in the model.

Table 15. Summary of multiple linear regression of inbound stream sample in West region

Residuals:

Min	1Q	Median	3Q	Max
-0.180	-0.045	-0.007	0.022	0.309

Coefficients:

	Estimate	Std. Error	t-value	P-value
(Intercept)	-8.169e-03	1.090e-01	-0.075	0.940
MHI	1.583e-05	3.159e-06	5.013	3.16e-06
MA	-2.927e-02	6.615e-03	-4.424	3.02e-05
PO	4.779e-08	8.014e-08	0.596	0.553

2.12 Outbound Contamination: West Region

In this subsection, a total of 88 old newspaper (ONP) samples and 22 old corrugated cardboard (OCC) samples were analyzed from five MRF facilities in the West region. The average rate of acceptable recovered material from the OCC and ONP samples were found to be 86.71% and 83.75%, respectively. Breakdowns of contamination rates in both OCC and ONP samples by acceptable recovered materials, outthrows and prohibitives are shown in Figures 23 and 24 below.

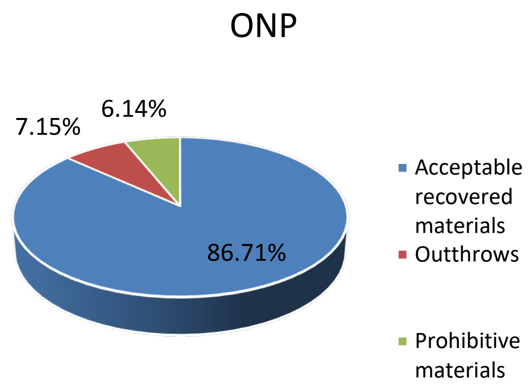

Figure 23. Breakdown of contamination in ONP

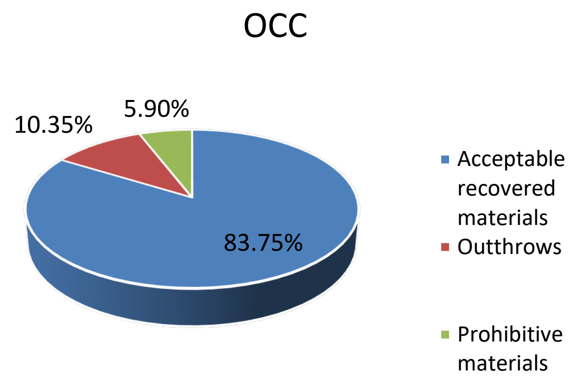

Figure 24. Breakdown of contamination in OCC

A descriptive analysis of the outbound contamination sample data by considered facilities are displayed in Table 16. A one-way ANOVA was performed to determine whether there are statistically significant differences between the contamination rate means in all facilities. 17 observations were recorded for each considered facility. ANOVA was performed using Microsoft Excel Data Analysis Tool and the results are shown in Table 17.

Table 16. Descriptive analysis of contamination rates by facility in the West region

	N	CR Mean	Std. Deviation	Std. Error	95% Confidence Interval for Mean		Min	Max
					Lower Bound	Upper Bound		
Facility 1	17	0.063	0.134	0.033	0.006	0.013	0.001	0.558
Facility 2	17	0.047	0.058	0.014	0.017	0.077	0.000	0.200
Facility 3	17	0.063	0.134	0.033	0.006	0.013	0.001	0.558
Facility 4	17	0.063	0.134	0.033	0.006	0.013	0.001	0.558
Facility 5	17	0.063	0.134	0.033	0.006	0.013	0.001	0.558

Table 17. ANOVA of outbound contamination by facility in the West region

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Groups	0.003	4	0.001	0.056	0.994	2.486
Within Groups	1.203	80	0.015			
Total	1.207	84				

In Table 17, the tested null hypothesis (H_0) is "having equal contamination rates across all facilities" while the alternative hypothesis (H_1) is "Not". The result shows that the $p - value$ of the hypothesis is greater than 0.05. Therefore, we fail to reject the null hypothesis and conclude that there is no statistically significant difference between the mean contamination rates in these facilities.

Figure 25 shows the total contamination rates for all samples combined (OCC and ONP) from the outbound stream against the paper mill allowable limits, where solid dot lines, solid lines, dash dot lines, and dash lines demonstrate the contamination rate, mean contamination rate, maximum allowable contamination rate by China, and maximum allowable contamination rate in the U.S., respectively. The mean contamination rates are shown to be higher than the maximum allowable limits by China. Also, contamination rates of majority of samples appear to be above the dash and dash dot lines, making them exceed the allowable limits provided by the paper mills in the U.S. (ISRI, 2013) and China (Janetsky,2018), rendering them as unacceptable. Figure 25 shows that at the individual level, 7.8% and 58.8% of the available samples pass the allowable contamination limits by China and U.S. paper mills.

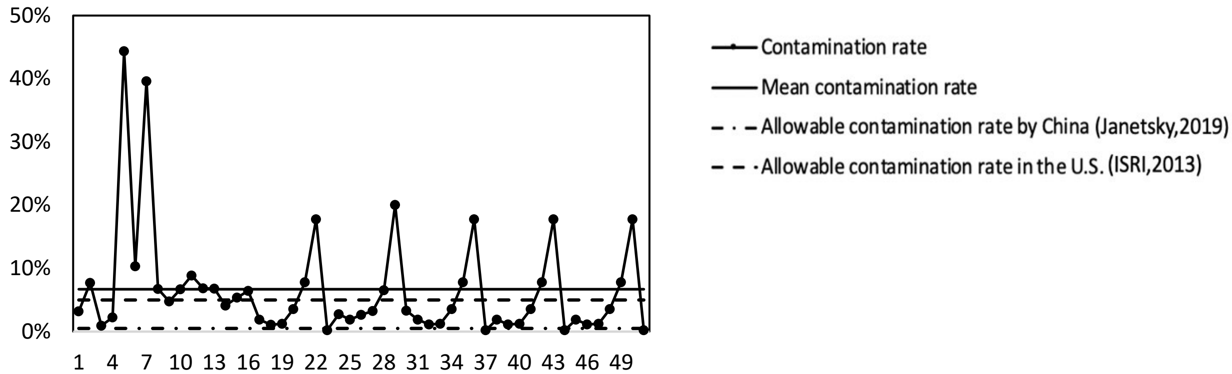

Figure 25. Total contamination analysis in West region outbound stream

Figures 26 and 27 display details of the composition of OCC and ONP in the outbound stream. OCC samples were found to be mostly contaminated by ONP and other mixed paper while the ONP samples were found to be mostly contaminated with OCC and other mixed paper. The tin cans make up for more than half of the prohibitive materials present in OCC and more than a quarter of the prohibitive materials in the ONP streams. Other paper accounts for 34% of prohibitive materials in OCC and 37% of prohibitive materials in OCC. Glass, film plastic and garbage represent 6% of prohibitive materials in OCC and 29% in ONP stream. While the amount of glass present in the OCC and ONP stream may be small, it could cause significant damage to the process, both in the short and long-term. For instance, 0.33% of glass in fiber stream has resulted in around $400,000 equipment damages in NORPAC Paper Mill. These expenses were due to the cleaning of poorly processed materials, repairing damaged equipment, more frequent equipment cleaning, equipment replacement and disposal of the residual materials that cannot be used (Morawski, 2009; GFSS, 2018).

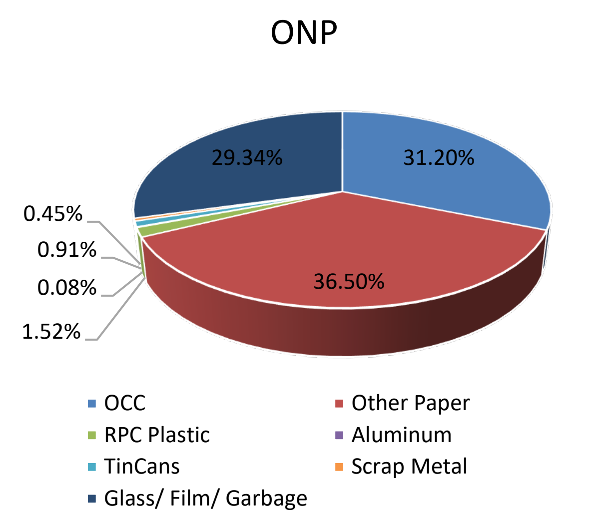

Figure 26. Prohibitive material analysis in ONP material stream

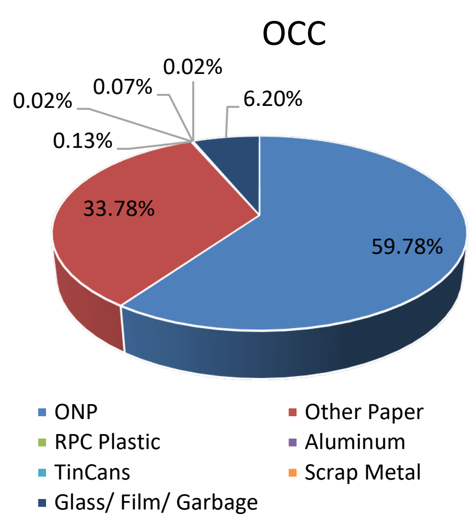

Figure 27. Prohibitive material analysis in OCC material stream

Task 3.0. Identify and evaluate new and promising collection and sorting methods to decrease contamination in SSR MRFs

Task 3.0. Objective

University of Miami will identify and evaluate alternative sorting practices and technology that may enable better separation of the materials during collection and within the MRF, respectively. Alternatives will be identified to include: (a) new technologies that have been already commercially used in some MRFs and offer promising results for reducing paper contamination, (b) state-of-the-art patents that have not been implemented yet but seem capable of decreasing contamination in MRFs, and (c) improved techniques for curbside collection that may eliminate the fiber material contamination at the source.

Task 3.0. Results

Best practices that can reduce the contamination in the inbound stream are investigated as part of this task. The first approach is to determine whether excluding a material from the total recyclables has an effect on the contamination rate. This was done by excluding glass materials from the total sample collected and then calculating the contamination rate. This contamination rate is then referred to as contamination rate excluding glass. Plastic materials are also excluded from the total sample collected and the contamination rate is then computed. This contamination rate is then referred to as contamination rate excluding plastic. We compare the mean contamination rates between total contamination, contamination rate excluding glass, and contamination rate excluding plastics using a t-test where the null hypothesis (H_0) is "the total contamination rate, contamination rate excluding glass, and contamination rate excluding plastics are equal" against the alternative hypothesis (H_1) that "at least one of the contamination rates is different". Table 18 shows the descriptive statistics of the alternatives with total contamination, contamination after excluding glass, and contamination after excluding plastic.

Table 18. Comparison of contamination rates after excluding glass and plastics

	Total contamination rate	*Contamination rate excluding glass*	*Contamination rate excluding plastic*
Mean	0.2112	0.2632	0.1937
Median	0.1961	0.2427	0.1766
Standard deviation	0.0962	0.1212	0.0996
Sample variance	0.0093	0.0147	0.0099
Count	60	60	60
Confidence level of means (95.0%)	0.0249	0.0313	0.02574

The means of total contamination rates and the contamination rates after excluding glass are compared using a t-test in order to determine whether the two has statistically significant differences. This comparison is shown in Table 19, where the $p-value$ of the hypothesis is found to be less than 0.05. Therefore, we reject the null hypothesis and conclude that there is a statistically significant difference between the means of total contamination rates and the contamination rates after excluding glass.

Table 19. Paired t-test results comparing total contamination rate with contamination rate excluding glass

	Total contamination rate	Contamination rate excluding glass
Mean	0.2113	0.2632
Variance	0.0093	0.0147
Observations	60	60
Pearson correlation	0.8774	

Hypothesized mean difference	0
df	59
t Stat	-6.8110
P(T<=t) one-tail	2.8233E-09
t Critical one-tail	1.6711
P(T<=t) two-tail	5.6466E-09
t Critical two-tail	2.0010

The means of contamination rates between total contamination and contamination after excluding plastic is also compared using a t-test in order to determine whether the two has statistically significant differences. This comparison is shown in Table 20, where the $p - value$ of the hypothesis is found to be less than 0.05. Therefore, we reject the null hypothesis and conclude that there is a statistically significant difference between the means of contamination rates before and after excluding plastic.

Table 20. Paired t-test results comparing total contamination rate with contamination rate excluding plastics

	Total contamination rate	Contamination rate excluding plastic
Mean	0.2113	0.1937
Variance	0.0093	0.0099
Observations	60	60
Pearson correlation	0.9830	
Hypothesized mean difference	0	
Df	59	
t Stat	7.4244	
P(T<=t) one-tail	2.5825E-10	
t Critical one-tail	1.6711	
P(T<=t) two-tail	5.1650E-10	
t Critical two-tail	2.0010	

3.1 Best Practices to Reduce Contamination

To facilitate improved recycling, this study discusses that the upgrading of the processing technology used in SSR systems may help reduce the levels of contamination in recyclables as the following.

Contamination by other recyclables: Recyclables present in the wrong material stream is found to be a major source of contamination. In the West region, ONP make up for more than half of the prohibitive materials present in OCC and steel tin cans make up for more than a quarter of the prohibitive materials in the ONP streams. Other paper accounts for 34% of prohibitive materials in OCC and 37% of prohibitive materials in ONP. While some recyclables are easy to screen out, others such as plastic bottles are no longer recyclable after passing through the initial processing step at the mill and instead may lead to a significant increase in the waste disposed. Therefore, ways to equip drivers with sensors or cameras that could scan the recyclable bins to detect nonrecyclables are encouraged. Using this technology could help drivers to detect bins with a high percentage of nonrecyclables and thereby drivers could skip such bins making these bins sent to trash (Commendatore, 2019). While this approach could be proven effective in determining what non-recyclables are dumped into the collection vehicle, the gain from this specific technology may be difficult to capture because those materials will still need to be sorted at the MRF. Compology stated that the implementation of cameras and sensors into the recyclables containers can decrease the nonrecyclable materials thrown in recyclables containers by as much as 80%. This technology embeds an accelerometer which triggers the cameras to take photos several times a day. In addition, when the container is lifted for dumping, an AI software analyzes the images to figure out how full the container is and whether any nonrecyclables are present (Metz, 2020). This technology may promise to be a viable deterrent if the cameras sound alarms and/or the offender is either required to correct his/her actions or is penalized. Enforcement or encouragement activities such as citations for violations on recycling have also been found to have some impact. For example, Westchester county enforced stringent recycling measures issuing fine to non-compliant participants and recorded an 18% increase in their recycling rate which can imply a lower contamination rate (Waste, 2019). Outreach and educational activities including having images on community announcements for better visualization have also shown promising results as many communities apply graphic instructions to carts. Can Manufacturers Institute recorded a 4.7% increase in recycling rate when implementing education and outreach alongside enhancing infrastructures (EPA, 2019). Wales which is the fourth best recycling country in the world has also credited their success to a comprehensive awareness campaign with an incentive-based system (BBVA, 2020). The Recycling Partnership's 2019 State of Curbside Survey data also shows that the average inbound contamination rates are lowest in communities where cart inspection and rejection methods are jointly implemented (Mouw et al, 2020).

Glass contamination: From the earlier detailed analysis of the composition of OCC and ONP in the outbound stream, glass was noted to be a major contaminant in both material streams. MRFs have been unable to separate glass into a marketable commodity in many cases as the glass is often broken to pieces or fines (very tiny pieces of glass). Broken glass is hard to separate from other recyclables, and even tiny bits of glass have the potential to contaminate the other materials, especially paper. Recovered paper sent to paper mills from single stream MRFs have reported to cause problems due to the abrasive qualities of glass embedded in the paper (CRI, 2016). Modified SSR programs that collect glass separately are found to report lower overall inbound glass contamination rates (CCG, 2020). Other practices including deposit and redemption systems have also shown reduction in the contamination rates based on a recent study (WWF, 2020). Disc screens can remove most of the glass and fine particles early in the recycling process to minimize belt wear and effectively separate glass from paper and OCC. Industry experts have estimated that disc screens can be about 90% effective in separating glass from OCC (Rogoff, 2014). Advanced materials sorting and processing capabilities in MRFs via rotating trommel c used in the removal of small size glass shards and installing mechanisms to prevent damage to the sorting equipment (e.g., mechanical sorters) (Biocycle, 2020) are also shown to be effective in reducing glass contamination. While these technologies have been installed on many MRFs to produce marketable glass, the value is low hence hauls to distant markets is impractical. As a result, a lot of the collected glass is not cleaned up and is used as daily landfill cover (Ellis,2019).

New MRF technologies: Some new technologies that are currently being used in MRFs also offer promising results in the reduction of paper contamination. Prohibitive materials, which comprise a major portion of contamination present in the paper bale, could be handled and removed in larger amount via disc screens and flotation tanks to remove inks (ASTRX, 2019). Separation of different density material via floatation systems also shows promise in terms of reducing the overall contamination within the incoming stream (Brzozowski, 2020). However, the use of flotation tanks may be better suited in the mills for pre-cleaning of the paper as MRFs make use of entirely dry processes. MRFs incorporating more advanced sorting technologies have also reported a 33% increase in the quality of their resultant recyclables (Bauer et. al., 2018; Paben, 2020). Other technologies that demonstrate reduction in contamination include (1) advanced optical technology and robotic sorters and (2) robots using sensory technology. Advanced technology optical and robotic sorters using advanced computer vision and machine learning sort materials more accurately. This technology also assists manual sorters and track the type of materials as well as quantity going through the recycling system (Peters, 2021). Waste Management Inc. made extensive facility upgrades in 2019 to twenty already existing MRFs by including non-wrapping screens, new optical sorting and robotics technology and new conveyors. This upgrade improved outbound paper quality by reducing OCC in the mixed-paper stream from 25% to less than 3%, and it also cleaned the aluminum and PET streams, bringing the company higher commodity prices for these materials (WM, 2020). Overall, the upgrades on the MRFs yielded an $11 increase in the value of the blended ton (Staub, 2020). Utilization of robots embedding sensory technology has also shown some promising results in the effort to improve the overall quality of recycled materials. These robots using sensory technology assist manual sorters to enhance efficiency and reduce the contaminants in recyclables as they are sorted in the facility. Prior to the implementation of this technology the conveyor belt was running at 140 feet per minute; using the robots, it was increased to 270 feet per minute thereby creating a better spread across the sorting belts between materials (Paben, 2019). A MRF in Indianapolis which had no sorting equipment was recently upgraded with optical sorters and reported a recovery rate of about 94% (Lovely, 2019).

Figure 28. Robots using sensory technology (Barker, 2020)

Figure 29. Optical sorters (Lovely,2019)

<u>Promising state-of-the-art patents:</u> Some state-of-the-art patents which are not currently widely implemented in MRFs but nonetheless are under exploration, may also help decrease contamination within recycling facilities. These technologies use electromagnetic and induction techniques (Brzozowski, 2020), solvent purification (Chasan, 2019) and specialized lasers (Staub, 2018) enabling better differentiation of recyclables from contaminants with results achieving 98% efficiency (Staub, 2020). While these technologies report increasing efficiencies in material differentiation and may plan key roles in future pre-cleaning of paper at a secondary processor or mill, their industrial adaptation to MRFs may need time. Equipping collection trucks and recyclable bins with sensors or cameras to detect nonrecyclables is also another recently proposed method which shows an 80% decrease in nonrecyclables present. This is achieved by signifying a customer of nonrecyclables present, thereby providing an avenue for rectifying this action and also creating a reward or penalty system (Commendatore, 2019). This technology, which is also known as a “smart bin” was patented in 2017 (Srivastava, 2017).

3.2 Cost Benefit Analysis

Paper mills observed their recovered fiber quality from SSR are being negatively impacted, resulting in increasing average net costs in comparison to DSR (AF&PA, 2008; Smalley, 2019). Previously, AF&PA reports (2008) assessed the impacts of recovered old newspaper costs across the three stages of collection, processing, and pulping and paper making where SSR is found to have significant cost savings in the collection stage at the expense of an increase in the processing and papermaking stage.

Table 21. Average costs of old newspaper across three stages comparing to DSR (US$/ton) (AF&PA, 2008)

	Collection	Processing	Pulping/papermaking	Net
Cost saving with SSR	$15 ($10-$20)			
Cost increase with SSR		$10 ($5-$15)	$8 ($5-$13)	$3 ($0-$8)

The market price for fiber materials seemed to have dropped significantly due to the implementation of the National Sword policies (Husock, 2020). The market conditions for recovered paper have also been impacted during the past year mostly due to COVID-19 pandemic. The price of recovered paper was on a steady rise with a peak price of $100 in May 2020 (Recycling Today, 2020). Due to the uncertainties surrounding the pandemic, generation of high grade paper dropped drastically with increased number of remote workers and the demand was even lower causing the prices of recovered paper to drop to $59 per ton as of August (Smalley, 2020). Cost benefit analysis was performed using the data obtained from (Smalley, 2020) and (UCRRA, 2020) in conjunction with data from SSR and DSR facilities in the South region to shed light onto the cost effectiveness of these collection programs. Table 22 below provides the cost benefit analysis performed for facilities using SSR versus DSR collection strategies along with the equation (1).

Table 22. Cost benefit analysis of SSR and DSR collection strategies

	Contamination rate as percentage (r)	Cost of recycling per ton (c)	Selling price of recycled paper 2017 (p_1)	Net income/(loss) per ton 2017 (n_1)	Selling price of recycled paper 2020 (p_2)	Net income/(loss) per ton 2020 (n_2)
SSR	18.50 %	$84.28	$103.00	$15.26	$59.00	$(20.60)
DSR	3.90 %	$81.00	$103.00	$21.14	$59.00	$(21.14)

The following formulas are used in the analysis:

$$n_t = (p_t - c) * (1 - r) \ where \ t = \{1, 2\} \quad (1)$$

One important result obtained in this pilot cost benefit analysis is that SSR, despite having significantly higher contamination rates, performed slightly better monetarily as the net loss incurred from SSR is lower than that of DSR in 2020. This performance may lead to important cost savings and revenues if the wide adoption of SSR in U.S. is considered (i.e., the results in Table 21 is provided on a per ton basis). Comparison of the net income obtained in 2017 prior to the implementation of National Sword policy on paper contamination levels to the net loss obtained in 2020 shows that these recent policies alongside the COVID-19 pandemic have notable effect on the paper recycling market. Furthermore, the improvements in new SSR technologies, and the volatility of selling price of recycled paper could denote even a higher potential for these systems in terms of their economic benefits.

Other Project Products

Products developed and technology transfer activities under this award are as the following:

a. Publications, conference papers, or other public releases of results.

- Runsewe, T., Bafail, O., & Celik, N. (2020) Performance Analysis of Waste Collection Programs in Material Recovery Facilities. In Proceedings of the IISE Annual Conference, New Orleans, Louisiana, Oct 31 – Nov 03, 2020.
- Runsewe, T., Damgacioglu, H., Perez, L., & Celik, N. (2021). Understanding Impact of Different Recycling Strategies on Contamination - An Inbound Contamination Analysis. Journal paper (working).

b. Web site or other Internet sites that reflect the results of this project:

- July 2020, Nurcin Celik and graduate student Temitope Runsewe presented as panelists at a REMADE webinar.
- July 2019, Nurcin Celik gave a REMADE Webinar on "Paper Recycling: Challenged by both Quality and Convenience".

c. Networks or collaborations fostered;

- December 2020, project progress has been presented at REMADE Annual Meeting 2020.
- June 2020, research team met with subject matter experts from the industry.
- October 2020, Temitope Runsewe was highlighted at the REMADE Graduate Student Spotlight.
- May 2020, project progress has been presented at REMADE Technology Summit Project Showcase.
- October 2019, project progress has been presented at REMADE Annual Meeting 2019.
- October 2019, Nurcin Celik gave an AF&PA Webinar Presentation on Issues of Contamination in Recycling Systems.
- Quarterly, project progress has been presented at REMADE TLC Committee Meetings.

e. Other products, such as data or databases, physical collections, audio or video, software or netware, models, educational aid or curricula, instruments or equipment.

- Microsoft access/SQL Database

Project Conclusions and Recommendations

The presence of contamination in the inbound stream not only impacts the quality of recovered products by reducing its value but also increases the processing cost (CCG, 2020). This contamination occurs as a result of the curbside collection programs used. This study analyzed the impact of various curbside collection programs on the contamination rates in the inbound streams using sample data collected from material composition studies, MRF audits and interviewing (in-person, e-mail, or phone conversations) for the regions studied. ANOVA was used to investigate the impact of SSR collection strategies on paper contamination in relation to alternative collection modes and determine to what degree the fiber contamination rates apply regionally. Regression analysis was then used to investigate the significant factors that contribute to increasing the contamination levels in the inbound stream.

Descriptive analysis on the available sample data from MRFs using both DSR and SSR showed that the mean and standard deviation of paper contamination rates in SSR systems (percent of total contamination) were higher than those of DSR systems. In the South region, the mean and standard deviation of the contamination rates were reported as 18.54% and 8.97%, respectively, for the SSR systems, both of which were higher than those of DSR contamination rates of 3.89% and 3.08%. In the North region, the mean and standard deviation of the contamination rates were reported as 3.59% and 3.16%, respectively, both of which were slightly higher than those of DSR contamination rates of 2.20% and 1.67%. The findings of this work showed that while SSR systems reported relatively higher contamination rates, these rates also spread over a wide range (high variances) suggesting that some SSR MRFs actually performed well (e.g., three facilities in the South region had a contamination rate of 5.98%, 7.56% and 7.70%, respectively).

ANOVA then revealed that there existed a significant statistical evidence that the mean contamination rates in SSR systems were higher than those of DSR in all regions at a significance level of more than 95% percent. The results from the correlation matrices also provided significant insight on the major statistical contributors to contamination allowing MRFs to identify the particular needs of their feeding SSR programs and seek measures that could help decrease their overall contamination rates.

Preliminary cost benefit analysis suggested that SSR systems were an economically viable and promising option in the South region considering all stages, despite having significantly higher contamination rates as the net loss incurred from SSR was found to be lower than that of DSR. This performance may lead to important cost savings and revenues if the wide adoption of SSR in U.S. is considered. Furthermore, the improvements in new SSR technologies, and the volatility of selling price of recycled paper could denote even a higher potential for these systems in terms of their economic benefits. Results of this study also provided valuable insight to current recycling practices and on how to potentially decrease contamination.

The future venues of this work involves itself with further investigations of causes of contamination and product quality in different recycling systems including collection compaction density, use of bins and other collection containers vs. carts, materials advertised as permitted in the collection stream, per capita expenditure on recycling education by community, MRF size and number of communities served by each MRF, private vs. publicly owned and operated MRF, age of MRF and throughput rates, contractual incentives to operator to increase recycling rate and quality, and changes in the body of the collected materials. The variation in the amount of contamination in the infeed and in the products across the range of SSR and DSR MRFs could also be examined to identify other factors nearly as important as DSR vs. SSR that affect those contamination rates.

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