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

by

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LIST OF ACRONYMS

AD	: Anderson-Darling normality test
AF&PA	: American Forest and Paper Association
ANOVA	: Analysis of variance
CR	: Contamination rates
C&D	: Construction and demolition
DOE	: Department of Energy
DSR	: Dual stream recycling
EPA	: Environmental Protection Agency
FDEP	: Florida Department of Environmental Protection
GHG	: Greenhouse gas
HDPE	: High density polyethylene
ISRI	: Institute of Scrap Recycling Industries
MANOVA	: Multivariate analysis of variance
MRF	: Material recovery facility
MSW	: Municipal solid waste
MWR	: Mixed waste recycling
NNMI	: National Network for Manufacturing Innovation
OCC	: Old corrugated containers
ONP	: Old newspapers
PET(E)	: Polyethylene terephthalate
RIT	: Rochester Institute of Technology
SSR	: Single stream recycling
TAG	: Technical awareness group
WTE	: Waste-to-energy

FINAL REPORT

(November 2016 - February 2017)

PROJECT TITLE:	Assessment of the Impact of Single Stream Recycling on Paper Contamination in Recovery Facilities and Paper Mills
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PROJECT WEBSITE:	http://www.coe.miami.edu/simlab/swm.html
COMPLETION DATE:	February 28th, 2017
TAG MEMBERS:	Jeremy O'Brien, Helena Solo- Gabriele, David Gregory, Paul Valenti, Lora Fleming, Alberto Caban-Martinez, Bryan Tindell, Sean Williams, Michael J. Fernandez, Brenda S. Clark, Patti Hamilton, Kenneth P. Capezzuto, Shihab Asfour, Ram Narasimhan, Samuel B. Levin, Stanley D. Gray, Patrick Sullivan, Michael Stark, Susan Warner, Himanshu Mehta, William Embree, Sally Palmi, Robert Gardner, Ron Hixson, Scott Harper, Leonard Marion.
KEY WORDS:	Single stream recycling, assessment of contamination rates, paper contamination, material recovery facilities, paper mills, prohibitive materials, outthrows

ABSTRACT

During the last decade, among all curbside collection programs, the use of single stream recycling (SSR) has been gaining popularity due to its inherent advantages in reducing collection costs and increasing community recycling participation. The percent of the United States population with access to SSR increased from 22% in 2005 to 73% in 2014, according to an American Forest & Paper Association (AF&PA) report (AF&PA, 2014). Recently in Florida, eight counties - Brevard, Broward, Charlotte, Collier, Escambia, Martin, Miami-Dade, and Okaloosa - have switched their recycling programs from dual stream recycling (DSR) to SSR. Compared to DSR, SSR makes collection easier and increases the amount of recyclables collected; however, SSR makes it more difficult and costly to separate the incoming waste once it reaches material recovery facilities (MRFs). With SSR, customers place non-recyclable materials (e.g., plastic bags, food waste) in single collection bins, which contaminates the recyclable materials in the waste stream. Broken glass, for example, contaminates the other commingled recyclables (especially paper) in the collection bins. This can damage equipment in the material recovery facilities as well as lower the quality of the end products. On the other hand, in a DSR system, which provides customers with two collection bins, customers separate paper products from the other glass, metal, and plastic recyclables. This separation results in lower inbound contamination rates compared to SSR. This study attempted to assess and evaluate the impact of SSR on contamination of the paper collected from various Florida counties.

Researchers sent 351 email requests and conducted 74 phone interviews to determine the inbound contamination rates of recyclables collected by Florida counties and cities. Fifteen counties around the state - Alachua, Brevard, Broward, Citrus, Escambia, Hillsborough, Indian River, Lee, Leon, Marion, Okaloosa, Pasco, Santa Rosa, Sarasota, and Seminole - provided their recyclable composition studies. By assessing those studies, researchers were able to determine contamination rates in 170 samples from SSR systems and 45 samples from DSR systems. Based on this data, the mean contamination rates were 18.54% for SSR and 3.89% for DSR. The data were further analyzed using one-factor analysis of variance (ANOVA) to test the statistical significance of the difference between the mean contamination rates of the two systems. Based on the ANOVA statistics, the difference in these contamination rates was found to be statistically significant.

The way that overall recycling rates are calculated can be misleading when the contamination rates are high. For this study, researchers developed a measure called “adjusted recycling rates,” which is a county’s remaining recycling rate after the inbound contamination rates are taken into consideration. Among the counties which use SSR, County 1 (refer to Section 5.3) had the largest recorded contamination rate with 28.2%. The measured recycling rate of that county was 58% in 2015. Since 28.2% of the total recyclables collected from the county was contaminated (and disposed of in landfills), the adjusted recycling rate for that county decreases the rate to 41.64%.

The smallest contamination rate among the SSR counties was 7.5% (County 11, refer to Section 5.3), in a county which reported an overall recycling rate of 35% in 2015. Since 35% of the total recyclables collected from the county was contaminated (and disposed of in landfills), the adjusted recycling rate for that county is reduced to 32.37%. Taking contamination rates into

consideration in analyzing recycling rates lowered the percentage difference between the recycling rates of the two counties from 23% (58% - 35%) to 9.27% (41.64% - 32.37%).

Further analysis was conducted for two SSR counties (for which the ANOVA was conducted with higher confidence due to the availability of data) to determine if the inbound contamination rates for different waste-generator sectors (single-family, multi-family, and commercial) were different. In the first county, single-family residences generated the highest reject rates, while the commercial sector had the lowest reject rate. With that knowledge, county officials can focus on educating single-family residents about which materials can go into single stream bins. In the second county, however, the reject rates of single-family, multi-family, and commercial sectors were not significantly different from each other based on ANOVA results. The mean reject rates, however, were the highest in the multi-family sector. Local officials can use this information to educate the managers and residents of multi-family complexes on how to reduce the reject rates in the SSR incoming stream.

To assess contamination in end products made from recycled material, researchers obtained 266 old newsprint (ONP) samples and 35 old corrugated cardboard (OCC) samples from four currently operating facilities in Florida. Average rates (weight of the contamination/total sample weight) of acceptable recovered material, brown paper, outthrows, and prohibitive materials in 266 samples from the ONP stream were 67.41%, 7.81%, 17.66%, and 7.13% respectively. Average rates of acceptable recovered material, outthrows, and prohibitive materials in 35 samples from the OCC stream were 91.12%, 3.75%, and 5.12%, respectively. Among 266 samples from the ONP stream, none of the samples could pass the paper mill standards due to the high rates of at least one of the contamination types (brown paper, outthrows, or prohibitive materials). Among 35 samples from the OCC stream, only 31.4% of samples had low enough contamination rates to meet the maximum allowable limits that paper mills set for both outthrows and prohibitive materials. Further analysis was conducted on the most common types of prohibitive materials in the OCC and the ONP streams. Residue, MRF film plastic, and high-density polyethylene (HDPE) were the most common types of prohibitive materials found in the OCC stream. In the ONP stream, residue, PET, and MRF film plastic were the most common types of prohibitive materials found. Material recovery facilities can improve process efficiency when the residue, MRF film plastic, HDPE, and polyethylene terephthalate (PET) are separated out from the OCC and the ONP streams.

Researchers within this study have developed the following conclusions based on their analysis in Florida:

- Inbound contamination rates of SSR are statistically significantly higher than DSR.
- Recycling rates of the counties that use SSR are much lower than the adjusted recycling rates of the same counties when the contamination rates are not taken into consideration.
- Problematic waste-generator sectors need to be identified for each county separately, and officials should focus on specific segments to provide appropriate outreach, education, and recycling guidance for each specific sector.
- There might be a higher potential to increase recycling rates in more densely populated counties. Results indicated that there was a statistically significant difference for newspaper and other paper recycling rates in Miami-Dade and Broward Counties before and after they switched to SSR.

- Among all material samples, acceptable rates of the OCC and the ONP were 91.12% and 67.41%, respectively. However, only 31.4% of 35 samples from the OCC stream passed the paper mill standards for all types of contamination. None of the 266 samples from the ONP stream satisfied the paper mill standards because of the high rates of at least one of the contamination types.
- Residue and MRF film plastic were among the most common prohibitive materials in both the OCC and the ONP streams.

METRICS:

1. List graduate student or postdoctoral researchers **funded** by **THIS** Hinkley Center project.

Last name, first name	Rank	Department	Professor	Institution
Yasar, Duygu	M.S. Student	Department of Industrial Engineering	Prof. Nurcin Celik	University of Miami
Damgacioglu, Haluk	Ph.D. Candidate	Department of Industrial Engineering	Prof. Nurcin Celik	University of Miami
Bastani, Mehrad	Ph.D. Candidate	Department of Industrial Engineering	Prof. Nurcin Celik	University of Miami

2. List undergraduate researchers working on **THIS** Hinkley Center project.

Last name, first name	Rank	Department	Professor	Institution
Guller, Alyssa	Undergraduate Student	Department of Industrial Engineering	Prof. Nurcin Celik	University of Miami

3. List research publications resulting from **THIS** Hinkley Center project (use format for publications as outlined in Section 1.13 of this Report Guide).
   - Yasar, D., Damgacioglu, H., Celik, N. "Assessment of the impact of single stream recycling on contamination rates in Florida," *working journal paper*.

4. List research presentations (as outlined in 1.13.6 of this Report Guide) resulting from **THIS** Hinkley Center project.
   - *Technical Awareness Group (TAG) I Meeting* took place on March 29th, 2016 at the McArthur Engineering Building of the University of Miami with 23 attendees (both on-site and via conference call).
   - *WM Meeting* took place on May 27th 2016 at Reuter Transfer Station located in 20701Pembroke Road Pembroke Pines, FL 33029.
   - *Resolute Forest Products (Atlas Paper Mills) Meeting* took place took place on November 9th, 2016 in 3725 East 10th Court Hialeah, FL. Our project was explained to James Balik, Environmental Manager and Julian de la Fuente, Process Engineer.
   - *Technical Awareness Group (TAG) II Meeting* took place on February 3rd, 2017 at the McArthur Engineering Building of the University of Miami with 16 attendees (both on-site and via conference call).

5. List of individuals who have referenced or cited publications from this project.
   - No publications to date.

6. How have the research results from **THIS** Hinkley Center project been leveraged to secure additional research funding?
   - PI Celik and her team (the efforts are led by Rochester Institute of Technology (RIT)'s Nabil Nasr) are awarded an institutional grant by Department of Energy (DOE)'s National Network for Manufacturing Innovation (NNMI) program (Project REMADE,

$70M awarded by DOE, $79M to be cost shared). PI Celik's research on the assessment of the impact of SSR on paper contamination is selected amongst the Consortium's foundational studies which will kick-start the efforts.

7. What new collaborations were initiated based on **THIS** Hinkley Center project?
    - Eddie McManus, Director of material recovery facilities owned by Waste Management in Florida, has been very helpful in providing necessary information. He will be the future direct point of contact if any further information from Waste Management is needed.
    - Jonathan Gold, a renowned expert in the paper recovery industry, has been very helpful in explaining how single stream collection affects the paper recycling industry. He has a wealth of experience in both the public and private paper recycling industries. He served as Senior Vice President of Newark Recovery and Recycling, Chairman of the AF&PA Paper Recovery Sector, Chairman of the ISRI Non-Metallic Division, and Chairman of the AF&PA and ISRI joint task force on paper recycling. We will be keeping him updated on the progress of our project.
    - Jim Balik, Environmental Manager for U.S. Pulp and Paper Operations at Resolute Forest Products (acquired Atlas Paper Mills), provided valuable information about single stream recycling's impact on the paper industry.
    - John Perry, Process Improvement Manager at Waste Management, Inc., hosted the research team at the Reuter Transfer Station in Pembroke Pines, FL. He discussed the issues the facility encounters from contamination in single stream recycling.
    - Julian de la Fuente, Process Engineer at Atlas Paper Mills in Hialeah, FL, helped us make the arrangements to host our team at Atlas Paper Mill.
    - Florin Gradinar, EHS Manager at Atlas Paper Mills in Hialeah, facilitated the arrangements for the team's visit to the Atlas Paper Mill and offered to contact the company's sister facilities to provide additional data.
    - Karen Moore, Environmental Administrator at the Florida Department of Environmental Protection (FDEP), has provided feedback on the progress and findings of our study.
    - Ramon Gavarrete, P.E., Engineer in Highlands County, and Larry Starkey, Operations Manager in the Marion County Solid Waste Division, has been very helpful in providing necessary data.
    - Johnny Edwards, P.E., Manager at the Seminole County Solid Waste Management Division, and Lisa Rubino, Program Coordinator at the Seminole County Solid Waste Management Division, provided us with a comprehensive report that analyzed the residue rates in Seminole County.
    - Sally Palmi, Solid Waste and Resource Recovery Director in Hernando County, has followed intently the findings of both last year's project, "Assessment of Advanced Solid Waste Management Technologies for Improved Recycling Rates," and our current project. She also serves on the TAG committee for the current project.
    - Paul Hurst, Recycling Coordinator for the City of Tallahassee, provided the 2014 Leon County Material Characterization study and valuable information on how the city measures the weights of sorted materials.
    - Jennifer L. Seney, Pasco County Recycling Coordinator, provided the waste characterization study conducted for Pasco County.

- Himanshu Mehta, Managing Director at the Indian River County Solid Waste Disposal District, provided Indian River County’s 2013 recyclables composition study (before they switched to single stream recycling).

8. How have the results from **THIS** Hinkley Center funded project been used (**not** will be used) by FDEP or other stakeholders? (1 paragraph maximum).
   - The results of this study have not yet been presented.

EXECUTIVE SUMMARY

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

PRINCIPAL INVESTIGATOR: Nurcin Celik, Ph.D.

AFFILIATION: Department of Industrial Engineering, University of Miami

PROJECT WEBSITE: http://www.coe.miami.edu/simlab/swm.html

TAG MEMBERS: Jeremy O'Brien, Helena Solo-Gabriele, David Gregory, Paul Valenti, Lora Fleming, Alberto Caban-Martinez, Bryan Tindell, Sean Williams, Michael J. Fernandez, Brenda S. Clark, Patti Hamilton, Kenneth P. Capezzuto, Shihab Asfour, Ram Narasimhan, Samuel B. Levin, Stanley D. Gray, Patrick Sullivan, Michael Stark, Susan Warner, Himanshu Mehta, William Embree, Sally Palmi, Robert Gardner, Ron Hixson, Scott Harper, Leonard Marion.

COMPLETION DATE: February 28th, 2017

OBJECTIVES:

During the last decade, SSR has gained popularity due to its inherent advantages in reducing collection costs and increasing community recycling participation. According to an AF&PA report, in 2005, only 22% of the United States population had access to SSR, and by 2014, 73% of the population had access to it (AF&PA, 2014). Recently, eight Florida counties - Brevard, Broward, Charlotte, Collier, Escambia, Martin, Miami-Dade, and Okaloosa - switched their recycling programs from DSR to SSR. Admittedly, SSR increases the amount of recyclables collected and eases the collection process, but it makes the material separation in material recovery facilities (MRFs) more difficult and costly. With SSR, people place more non-recyclable materials (e.g., plastic bags, food waste) in single collection bins, which contaminates the recyclable materials in the stream. DSR, on the other hand, provides customers with two collection bins to separate paper waste from other recyclables (glass, metal, and plastics). This study assessed and evaluated the impact of paper contamination in SSR versus DSR in various Florida counties. Researchers sent 351 email requests and conducted 74 phone interviews to record the inbound contamination rates of recyclables collected by Florida counties and cities. Fifteen Florida counties - Alachua, Brevard, Broward, Citrus, Escambia, Hillsborough, Indian River, Lee, Leon, Marion, Okaloosa, Pasco, Santa Rosa, Sarasota, and Seminole - provided recyclable composition studies. The data were analyzed using one-factor ANOVA to test the statistical significance of the difference between the mean contamination rates of the two systems, and the difference was found to be significant. Further analysis was conducted on the contamination rates of three waste-generator sectors: single-family, multi-family, and commercial. Counties should identify problematic waste generator sectors with high contamination rates and focus on specific methods to educate customers on recycling programs.

Finally, statistical analysis was performed for the OCC and the ONP material streams of four operating facilities in Florida. Among 266 samples from the ONP stream, none of the samples could pass the paper mill quality standards due to the high rates of at least one of the contamination types (brown paper, outthrows, or prohibitive materials). Among 35 samples from the OCC stream, only 31.4% of samples could pass the paper mill quality standards for both outthrows and prohibitive materials.

METHODOLOGY:

The study consisted of the following phases:

1. Collection and Analysis of Contamination Rates in SSR and DSR in Inbound Material Stream: To identify and assess whether SSR has a significant impact on paper contamination rates, researchers compared the contamination rates in different types of MRFs. Recognizing that there was an absence of data for contamination rates in public resources because of commercial sensitivity, the team's researchers sent 351 email requests and conducted 74 phone interviews to obtain inbound contamination rates of recyclables collected by Florida counties and cities. Alachua, Brevard, Broward, Citrus, Escambia, Hillsborough, Indian River, Lee, Leon, Marion, Okaloosa, Pasco, Santa Rosa, Sarasota, and Seminole counties provided their local recyclable composition studies. Contamination rates were then retrieved from 16 recyclable composition studies that contained 170 individual samples from SSR and 45 individual samples from DSR systems. The mean contamination rates were found to be 18.54% for samples from SSR and 3.89% for samples from DSR. The data were further analyzed using ANOVA to determine whether the difference between the mean contaminations of the two systems were statistically significant. The analysis found that the difference was in fact significant.
2. Assessment of Waste Generator Sectors: Reject rates in the incoming stream from three generator sectors - single-family residential, multi-family residential, and commercial - were analyzed for two comparable counties which switched to single stream recycling in recent years. The counties have similar socio-economic characteristics. Our analysis on the first county revealed a statistically significant difference in reject rates among the three waste generator sectors. In the second county, the results indicated no statistical evidence for the difference in reject rates from these sectors, but based on the descriptive statistics, some insights were provided about ways that the two counties could decrease reject rates. The two counties should develop different programs and incentives. For example, the first county should target single-family residences while the second one should educate and assist the owners or managers of multi-family residences. More importantly, the approximately 50% reject rate in the first county was much higher than the reject rate of the second county, which was approximately 14%. This shows that counties which are similar to the first county should focus on educational and/or technical programs for all sectors in order to decrease the reject rates.
3. Assessment of Adjusted Recycling Rates: The largest contamination rate among the counties that use SSR (and provided recyclable composition reports for this study) was 28.2%. The reported recycling rate of this county was 58% in 2015. Considering the amount of contaminated materials that were rejected from the recyclable waste stream, the actual recycling rate was calculated at 41.64%. In the county with the smallest contamination rate - 7.5% - the recycling rate was reported at 35% in 2015. Again, considering the amount of contaminated materials that were rejected from the recyclable waste stream, the actual

recycling rate was calculated at 32.37%. Taking contamination rates into consideration to compute recycling rates lowered the percent difference of the recycling rates of the two counties from 23% (58% - 35%) to 9.27% (41.64% - 32.37%). One assumption made for the calculation of adjusted recycling rates was that all recyclables collected are sent to an SSR MRF to be processed. Calculating recycling rates can be misleading when the contamination rates are high. By not including contamination rates in their reported overall recycling rate numbers, the impact that SSR has on overall recycling rates might be misrepresented. This may further misinform decision makers, who may end up giving communities credit for high recycling rates when, in fact, much of the material ended up in the landfill. Not including contamination rates also affects programs that aim to improve recycling rates in these counties.

4. Collection and Analysis of Recovered Paper Contamination Rates in Outbound Material Stream: The OCC and ONP audits conducted in 2016 were obtained from four Florida operating facilities. Average rates (weight of the contamination/total sample weight) of acceptable recovered material, brown paper, outthrows, and prohibitive materials in the 266 samples from the ONP stream were 67.41%, 7.81%, 17.66%, and 7.13% respectively. Among 266 samples from the ONP stream, none of the samples could pass the paper mill standards due to the high rates of at least one of the contamination types (brown paper, outthrows, or prohibitive materials). Average rates of acceptable recovered material, outthrows, and prohibitive materials in 35 samples from the OCC stream were 91.12%, 3.75%, and 5.12%, respectively. Among 35 samples from the OCC stream, only 31.4% of samples had low enough contamination rates (for both outthrows and prohibitive materials) to meet the limits set by the paper mills. The most common types of prohibitive materials in the OCC and the ONP streams were residue, MRF film plastic, high-density HDPE and PET. MRF operators can improve process efficiency when the residue, MRF film plastic, HDPE, and polyethylene terephthalate (PET) are separated from the OCC and the ONP streams.

RESEARCH TEAM

Nurcin Celik (P.I.) is an Associate Professor in the Department of Industrial Engineering at the University of Miami. She received her M.S. and Ph.D. degrees in Systems and Industrial Engineering from the University of Arizona. Her research interests lie in the areas of integrated modeling and decision making for large-scale, complex, and dynamic systems such as solid waste management systems and electric power networks. She received the Presidential Early Career Award for Scientists and Engineers in 2017 by the White House. This is the highest honor bestowed by the U.S. government on outstanding scientists and engineers beginning their independent careers. She has also received many other awards including the IAMOT Young Investigator Award (2016), Eliahu I. Jury Career Research Award (2014), AFOSR Young Investigator Research Award (2013), University of Miami Provost Award (2011, 2016), IAMOT Outstanding Research Project Award (2011), IERC Best Ph.D. Scientific Poster Award (2009), and Diversity in Science and Engineering Award from Women in Science and Engineering Program (2007). She can be reached at celik@miami.edu.

Duygu Yasar is a graduate student in the Department of Industrial Engineering at the University of Miami. She earned her bachelor's degree in Industrial Engineering from Yildiz Technical University, Turkey. She graduated in the top 5% of her class. Her research interests revolve around sustainable systems with a focus on large-scale solid waste systems, evaluation of solid waste management technologies, multi-criteria decision analysis, data analytics in large scale systems, and modeling of integrated large-scale and complex systems. She can be reached at duyguyasar@miami.edu.

Haluk Damgacioglu is a Ph.D. candidate in the Department of Industrial Engineering at the University of Miami. He received a B.S. and a M.S in Industrial Engineering from the Middle East Technical University in Turkey. He has received several awards including the 2016 University of Miami GSA Academic Excellence, Leadership and Service Award and 2015 ICCS Best Workshop Paper Award. His research interests lie broadly in application of dynamic data driven adaptive simulations and simulation optimization under uncertainty. His email address is haluk.damgacioglu@miami.edu.

Mehrad Bastani is a Ph.D. candidate in the Department of Industrial Engineering at the University of Miami. His research interests include applied probability and statistical modeling, and large-scale simulation-optimization techniques. He earned his bachelor's degree from the Department of Industrial Engineering at the Sharif University of Technology, Iran in September of 2011. He also earned his master's degree in Industrial Engineering at the University of Tehran, Iran in July of 2013. Mehrad was a recipient of the Computer and Information Systems Division Best Student Paper at the Industrial and Systems Engineering Research Conference in 2015. He can be reached at m.bastani@umiami.edu.

DISSEMINATION ACTIVITIES

JOURNAL PAPERS AND BOOK CHAPTERS:

1. Yasar, D., Celik, N. "Assessment of the impact of single stream recycling on paper contamination rates in Florida," working journal paper.

PRESENTATIONS AND SITE VISITS:

1. *TAG I Meeting:* The first TAG meeting took place on March 29, 2016 at the McArthur Engineering Building of the University of Miami with 23 attendees. A conference call for those who wanted to attend the meeting remotely was established. Several comments made during the first TAG meeting were recorded.
2. *Waste Management, Inc. Meeting:* The meeting took place on May 27, 2016 at the Reuter Transfer Station, located at 20701 Pembroke Road in Pembroke Pines, FL. The project was outlined for John Perry, Process Improvement Manager.
3. *Resolute Forest Products (Atlas Paper Mills) Meeting:* The meeting took place on November 9, 2016 at 3725 East 10th Court in Hialeah, FL. We discussed the details of our project along with the needed data with James Balik, Environmental Manager, and Julian de la Fuente, Process Engineer. We gained important insights concerning how the recovered paper quality affects the quality of end-products, the ongoing competition between China and United States mills to purchase quality recovered paper, and what the mills do with the rejects.
4. *TAG II Meeting:* The second TAG meeting took place on February 3, 2017 at the McArthur Engineering Building at the University of Miami with 16 attendees. A conference call for those who wanted to attend the meeting remotely was established. Multiple comments were offered during the second TAG meeting.

FIGURE 1. Waste Management, Inc. meeting at Reuter transfer station: a) Material sampling station. b) Tipping floor. c) Duygu Yasar, John Perry, Nurcin Celik (from left to right).

TAG MEETINGS:

The project team hosted two TAG meetings on March 29, 2016 and on February 3, 2017.

WEBSITE: The team created and posted an enhanced website describing the project, accessible at http://www.coe.miami.edu/simlab/swm.html.

1 INTRODUCTION

Over the past two decades, the amount of municipal solid waste (MSW) produced in the United States – and particularly in Florida - has increased by over 73%, a significant uptick (EPA, 2017). In response to this tremendous increase in the waste stream, curbside recycling programs have been implemented throughout the United States in recent years. However, implementing a recycling program is quite challenging in light of economic and environmental issues affecting the large-scale, complex, and dynamic nature of the solid waste management system. Different types of collection systems, including mixed waste recycling (MWR), single stream recycling (SSR), and dual stream recycling (DSR) have been established as curbside recycling programs. Among them, the use of SSR has been increasingly used to reduce collection cost and increase community participation, as shown in Figure 2.

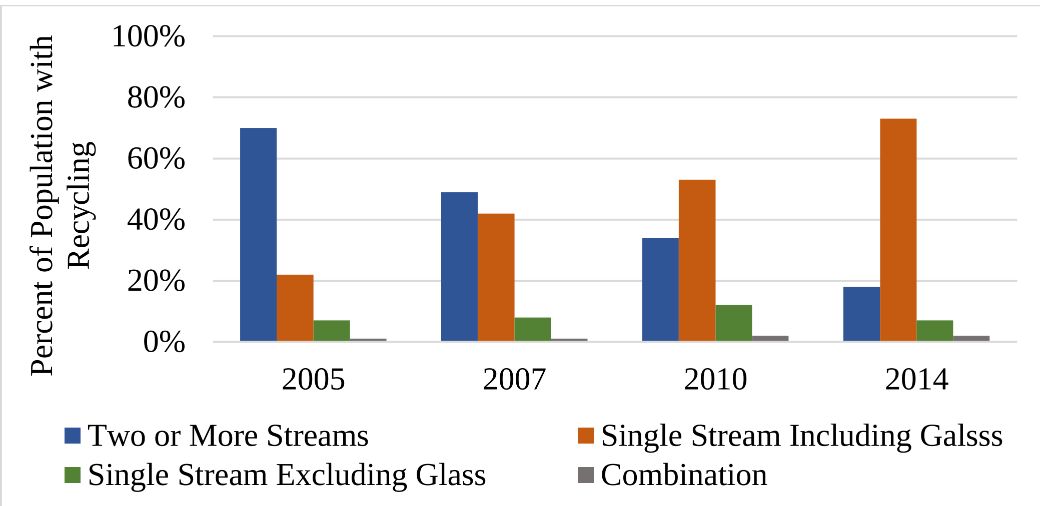

FIGURE 2. Paper/paperboard collection techniques (AF&PA, 2014).

In SSR systems, all recyclables are separated from MSW into a sole compartment in a collection truck. Collecting recyclables in a single compartment reduces collection cost by utilizing single driver trucks, it increases participation rates and the amount of collected recyclables. However, SSR systems operate with several drawbacks: higher contamination rates in the incoming stream which initially reach the processing facilities, 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). In the case of paper recycling, glass, plastic bags, and increasing amounts of food-waste in the incoming comingled stream negatively impact the quality of recycled paper. Compared to SSR systems, in DSR systems, two collection bins are provided for customers to separate paper from other recyclables (glass, metal, plastics). While collecting paper and other recyclables in two separate bins increases collection costs, DSR has lower paper contamination rates compared to SSR. While the average residue rate in dual-stream MRFs in the United States is 6.79% (including glass), this rate increases in single stream MRFs to 11.71% (AF&PA, 2014). When contamination rates increase in inbound waste streams, it negatively affects the recovered material quality as well as operation and processing costs. A 2004 study conducted by AF&PA (AF&PA, 2004) concluded that switching from DSR to SSR increases the average net cost by $3 per ton of recovered fiber for the entire value chain (collection, processing, and papermaking). In this project, we assessed the contamination rates in paper recycling considering MRF and paper mills operations. Inbound contamination rates, measured after recyclables were collected from counties and, before processed at MRFs, were analyzed to capture the difference between contamination rates in SSR and DSR. Outbound contamination rates, measured after recyclables are processed at MRFs, were analyzed to calculate the average rates of acceptable paper for each grade (ONP and OCC) based on the quality standards of the paper mills.

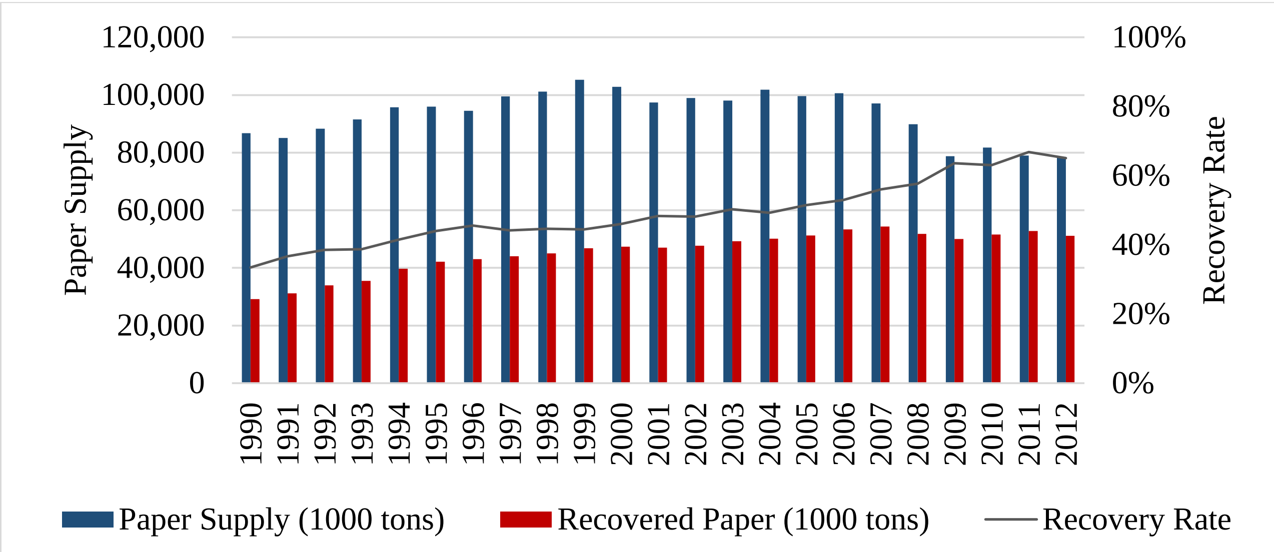

FIGURE 3. United States paper statistics during 1990-2012 (AF&PA, 2014).

There is a growing trend in paper supply and recovery rates in the United States since 1990 as shown in Figure 3. Should the measure of a recycling program's success be based solely on looking at the amount collected? Or are there further recyclable materials lost along the whole material recovery process which are not taken into consideration when calculating recovery rates? These questions are becoming more and more controversial in the paper industry, especially in parts of the United States, including Florida, where SSR has been adopted by numerous counties. The basic process flow for paper recycling is shown in Figure 4.

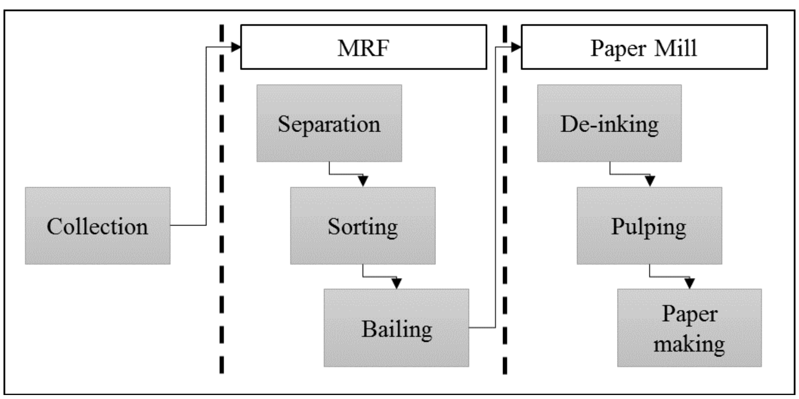

FIGURE 4. Basic paper recycling process flow from collection to processing in paper mills.

After collection, paper and other recyclables are sent to MRFs. In MRFs, paper is first separated from other materials and then sorted based on grade. The United States Department of Commerce divides paper into five basic paper grade categories given as the following (Forstall, 2002):

- **Corrugated:** Old corrugated containers (OCC), solid fiber boxes, container plant clippings, craft paper and bags, bag clippings, carrier stock, and carrier stock clippings are included under the corrugated category, which is the largest source of waste paper (Forstall, 2002). Main collection sources of corrugated material are retail establishments, factories, and office buildings.
- **Newspapers:** The second-largest source of waste paper is newspaper. Old newspapers (ONP), special news, white blank news, ground-wood computer printout, publication blanks, mixed ground wood and flyleaf shavings, and coated ground wood sections are included in this category (Forstall, 2002).
- **Mixed Paper:** This source consists of paperboard, discarded mail, telephone directories, and magazines where they are used to produce paperboard and tissue, as a secondary fiber in new paper production, or as a raw material in non-paper products such as gypsum wallboard, chipboard, roofing felt, cellulose insulation, and molded pulp products (such as egg cartons).
- **High Grade Deinked Paper:** This source consists of high grade paper, including letterhead, copier paper, envelopes, and printer and convertor scrap that has gone through the printing process.
- **Pulp Substitutes:** This source includes high grade papers, including shavings and clippings from converting operations at paper mills and print shops. They are used in place of virgin materials to produce high grade paper products.

In SSR, all recyclables are commingled in one collection bin, and the contamination of paper by other recyclables in the stream (metal, glass, and plastic) is a challenging problem. MRFs regularly separate heavyweight contaminants, such as glass, plastic containers, steel cans, etc., using cleaning and screening processes. There are also several stages in the MRFs which are designed to remove any trapped metals. Here, the most challenging task for recycling paper is removing specific materials like plastics and other polymer materials known as “stickies.” A single plastic bag can create thousands of tiny particles which are quite challenging to remove by screening or cleaning. If those small particles of plastic end up in a paper sheet, they cause deficiencies and downgrade the quality of the product. If the levels of other materials exceed the maximum specified amount for each grade of paper, the recovered fiber material is no longer tolerable and it is either downgraded to a lower paper grade - resulting in a lower selling price (Lasmarias et al., 2003) - or it is classified as valueless and appropriate only for disposal. When the poor quality paper has to be sent to the landfills, papermaking costs for paper mills increase since they are handling materials that are not even used in their process.

Another major concern with single stream recovered paper is that paper grades can mix, combining bleachable material (i.e., old newspapers and white papers) with un-bleachable material (i.e., old corrugated containers and boxboard). Here, bleaching increases the brightness of the pulps in paper mills to yield high-quality printing paper (SCA, 2010). When working with recycled paper, the quality of the produced paper is always less than the ingredient paper because fibers are gradually shortened after repeated recycling and become weaker (SCA, 2010). As the machine converts the recycled paper back into pulp, it beats the fiber, which causes the strands to break. Even though making paper from recycled material is more complicated than creating paper from virgin material, a large percentage of the paper produced comes from recycled paper since the same fibers can be used five to seven times before they become too short (Environmental Protection Agency [EPA], 2014). This can potentially save forests since it becomes more resource-efficient as the high-grade scrap paper is recovered to produce printing and writing paper, where the fibers can be reused many times (Conservatree, 2016). Recovered high-grade (printing and writing paper) can be used to produce most other grades, but the process to make the high-grade products will not tolerate much paper from other grades (Conservatree, 2016). When the paper grade is higher, it also becomes harder to recover it through recycling. For example, in 2013, the recovery rate for high-grade deinked paper was approximately 50% while the recovery rate for old corrugated containers was approximately 90% (see Figure 5).

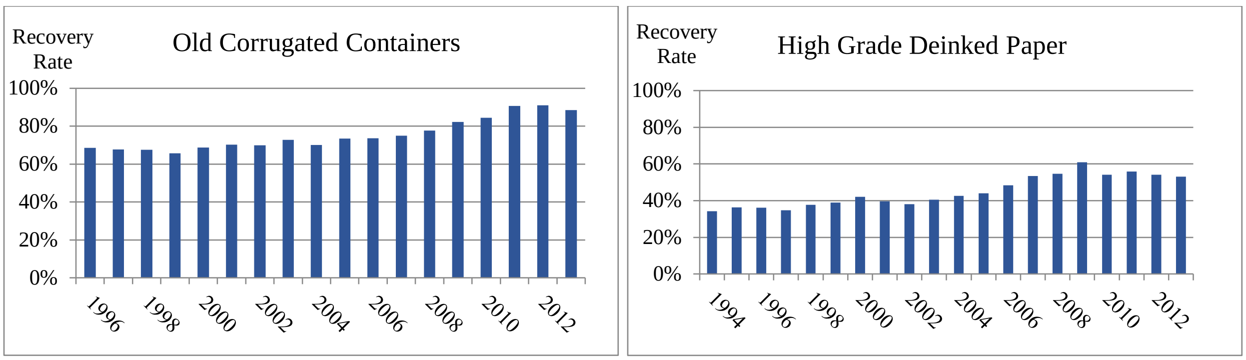

FIGURE 5. Recovery rates of old corrugated containers and high grade deinked paper during 1996-2012.

High contamination also adds to the landfill costs of paper mills/processors. Figure 6 shows the change of contamination rates and landfill costs after the suppliers of Blue Heron Paper Company started to switch to SSR in 1998. Landfill costs increased in parallel with the increased contamination rates. A new automated sorting system established in 2003 lowered contamination rates and landfill costs. Table 1 shows the changes made in the company's feedstock supply during this period.

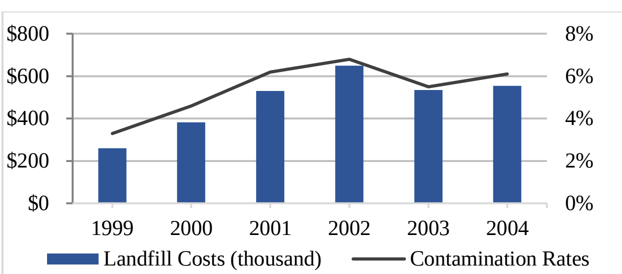

FIGURE 6. Blue Heron Paper Company's contamination rates (Kinsella, S., 2006).

TABLE 1. Changes made in the feedstock of Blue Heron Paper Company.

Years	Event
1998	▪ Supplier city switched to SSR ▪ From 14 separate to all except glass
1999 - 2001	▪ Other cities followed ▪ Manual sorting on old lines continued
2002 - 2003	▪ New automated sorting systems ▪ Equipment improvements at the mill

Just as indicated in the Blue Heron Paper Company's example, increased contamination rates contribute to the landfill costs of paper processors/mills, and, when the contamination levels are very high, paper removed from one community may end up in the landfill of another community. The impact of SSR on paper contamination in recovery facilities and paper mills needs to be investigated to determine the extent that SSR is responsible for contamination (at high or low levels).

2 BACKGROUND AND LITERATURE REVIEW

In SSR systems, customers use a single all-purpose bin to collect recyclables. The method is known as an easy way to increase recycling rates compared to multiple stream recycling. Studies in the San Francisco Bay area have concluded that consumers prefer to use the single stream system because it does not involve a cumbersome sorting process at the individual level (Wang, 2006). In SSR, MRFs are responsible for separating all recyclables after the recyclables are collected from the community. While such a system may increase the amount of recyclable material collected, it increases the contamination in the waste that goes to MRFs. Contamination is a controversial issue and has proven to cause impacts on recycling, especially paper recycling. If, for example, a container contains biological material such as a stained paper plate, it may leak over onto other clean pieces of paper. Paper grade sorting is also paramount in determining the success of recycling systems. If all the paper is in one container, it becomes increasingly difficult to accurately separate the paper grades, which lowers paper pulp quality. This reduction decreases the number of times a paper can be recycled. It has yet to be studied whether the benefits of implementing SSR outweigh the costs. When all collection and processing costs at MRFs and paper mills were taken into account, a study conducted by AF&PA (2004) concluded that SSR is more costly for paper recycling than it is for multi-stream recycling.

Several studies compare various types of multi-stream recycling systems with single stream recycling based on different aspects of the recycling programs. Oskamp et al. (1996) analyzed commingled (single stream) and separated curbside recycling programs in terms of long-term participation rates. Two adjacent middle-class residential suburbs of Los Angeles that were significantly similar demographically, economically, historically, and culturally were selected as study sites. The city with the commingled recycling program accepts a much wider range of recyclables, including newspapers, magazines, junk mail, white and mixed paper, cardboard, corrugated cardboard, tin and aluminum cans, glass containers, plastic containers, metal foil, plastic bags, milk cartons, etc., while the other city collects only newspaper, glass, plastic, and tin and aluminum cans. The findings of the study are shown in Figure 7.

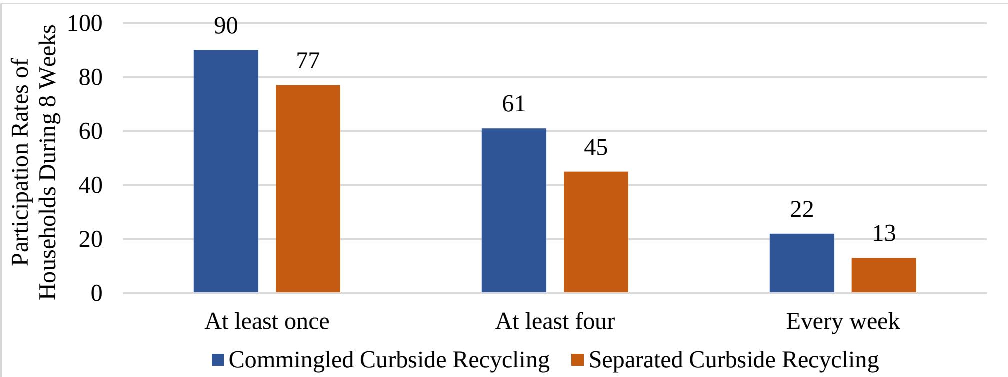

FIGURE 7. Participation rates of households during eight weeks of study (Oskamp et al., 1996).

As seen in the Figure 7, the participation rate of a commingled recycling program is significantly higher than for the separated program. Further findings of the study (Oskamp et al., 1996) are as follows:

- There is a significant difference between the two recycling programs in terms of the average weekly quantity recycled. The average participation in the commingled program was found to be 58% with an average weekly quantity recycled (by each of 608 houses) of 32.1 gallons per week. On the other hand, the participation rate was 42% in the separated program, with an average weekly quantity recycled (by each one of 613 houses) of 5.5 gallons per week.
- The contamination rates did not differ notably between the two programs. The contamination rates in the recycling bins of households that participated at least once during eight weeks was 8% in the commingled program, while it was 11% in the separated recycling program.

While the findings of the study showed that the commingled stream provides better results than the separated curbside recycling in terms of participation and contamination rates, it should be noted that there were challenges and limitations, including the fact that the results cannot be generalized for all cities because each community behaves differently.

Mueller (2013) analyzed the two recycling programs from a broader perspective to determine the most important factors that were associated with higher material recovery rates, including bag limits, user pay programs, the types of materials collected, curbside collection frequency, promotion and education activities, and the type of recycling collection stream (single stream and multi stream collection). The author collected data from 223 recycling programs in Ontario between 2005 and 2010, evaluating the effect of each policy on recovery rates through a combination of t-tests and multiple regression analyses. The study provided important implications about the relationship between the type of recycling collection stream and the recovery rate. A t-test was performed to determine the effects of single stream and multi stream collection on recovery rates. The statistical test results are shown in Figure 8. Even though the results show an increase in the recovery rates in the SSR collection system, regression analysis identified no statistical evidence showing a correlation between SSR and the higher recovery rates. It was concluded that the decision to select single stream or multi stream collection strongly depends on the availability or proximity of single stream MRFs rather than a community's desire to increase the recovery rates (Mueller, 2013).

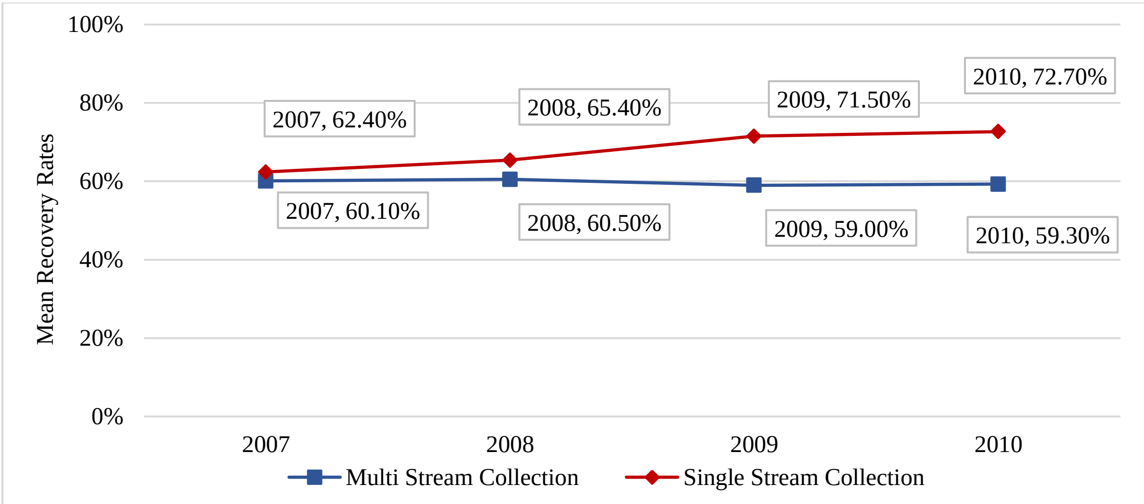

FIGURE 8. Mean recovery rates of multi stream and single stream collection systems in Ontario.

In addition to the studies (Oskamp et al., 1996 and Mueller, 2013) that compare DSR and SSR collection systems in terms of public participation and recovery rates, Fitzgerald et al. (2012) analyzed these systems based on greenhouse gas (GHG) emissions, or their "carbon footprint." The authors selected three medium-sized counties which had been converted from DSR to SSR. Their data included the tonnage of collected recyclables, monthly fuel consumptions, and emissions released from those counties' SSR operations. The study also analyzed the GHG emissions from energy and fuel consumption at MRF operations. The study concluded that SSR (collection and separation) provides remarkable GHG emission benefits over DSR.

In the literature, several research studies have discussed the benefits of SSR over DSR from different points of view as exemplified here by the studies of Oskamp et al. (1996), Mueller (2013), and Fitzgerald et al. (2012). However, there are several drawbacks to SSR collection, such as decreased quality of recovered materials; a gap in the literature on this point was partially filled by Miranda et al. (2013), who conducted two comprehensive studies before and after the installation of a new MRF. The studies analyzed the recovered paper quality of the largest Spanish newsprint mill (300,000 tons/year) and the effect of the new MRF (one of the largest single line MRFs in Europe with a capacity of 120,000 tons/year, at an investment of $9 million) on the recovered paper quality. The quality of recovered paper was determined by gravimetric analysis (measurement of mass as an analytical signal), which measures unusable materials from selected samples of recovered paper. The first study analyzed 191 samples collected during May 2008 to June 2009, when the recovered paper supplier bought the paper from a number of MRF stations in the United Kingdom. The second study analyzed 327 samples during 2009 when the supplier built its own MRF with modern sorting technologies to improve the quality of paper. The findings of the study are shown in Figure 9. Based on the results, the authors concluded that the most important requirement for sustainable recycling are source segregation and separate collection.

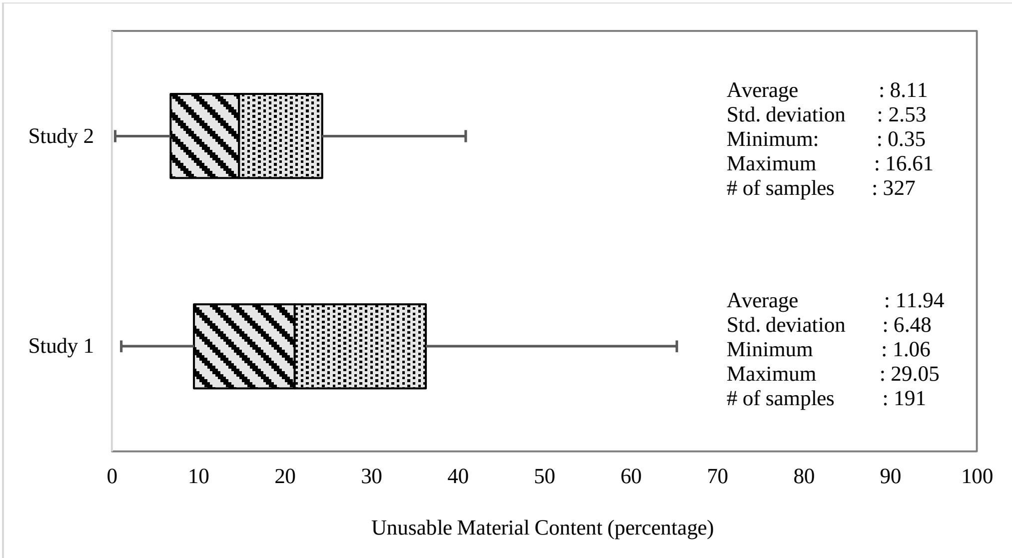

FIGURE 9. Statistical analysis results of the Miranda et al. (2013) study before and after the installation of new MRF.

Further findings of the Miranda et al. (2013) study include:

- The installation of the new MRF improved the quality of recovered products.
- The average and median unusable material contents were reduced by 32%.
- The percentage of samples with unusable material contents lower than 10% increased from 36.0% in Study 1 to as high as 80.2% in Study 2.

Beck (2006) compared the residual levels in four types of MRFs, the multi stream, single stream, mixed waste processing, and construction and demolition (C&D). A total of 77 MRFs in California were examined in this study. Results revealed that multi stream processing facilities have the least residual percentage (6%) with less moisture and food contamination within the fiber material than expected while the residual rate for SSR was found to be 14% and typically ranged between 2% and 50%.

Cascadia Consulting Group, Inc. (2006) analyzed the incoming commingled recyclables in single stream MRFs without comparing SSR to other types of systems mentioned in the previous studies cited. A total of 100 samples from four Puget Sound MRFs were collected to examine the composition of the incoming commingled recyclables, and all the collected samples were analyzed for the amount of residuals disposed of in landfills for four products (newspaper, mixed paper, polyethylene terephthalate (PETE), and glass). Here, the outbound material composition analysis allows MRFs to have an insight about the quality of recycled materials they sell to their customers and the amount and types of rejects that are disposed in landfills. The average contamination rate of four MRFs was 7.3% (29,800 tons) in the incoming commingled material stream where the individual contamination rates ranged between 3% and 10%. Even though the MRFs achieved a 98% recovery rate of incoming recyclables, the rest of the incoming stream was still disposed of in landfills. 23.7% of total residuals that were disposed of in landfills were recyclable materials. Furthermore, MRF operators concluded that the glass should be collected in a separate stream since it poses major mechanical and economic challenges for recycling, despite the fact that it constitutes only 7% of the incoming stream. Figure 10 shows the composition of newspaper and mixed paper before shipment to customers.

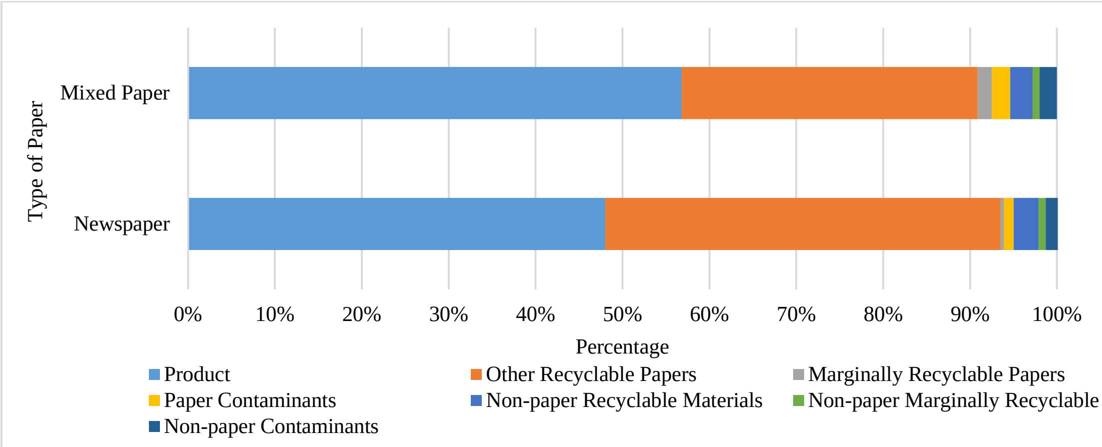

FIGURE 10. Material composition of processed newspaper and mixed paper in the Cascadia Consulting Group, Inc. (2006) study.

Another in-depth material composition analysis was conducted by Beck (2005) for curbside, drop-off, dual stream, and single stream recyclables in Pennsylvania. Unlike the Cascadia Consulting Group, Inc. study, where only SSR was examined, Beck compared different collection programs with respect to the composition of recyclables. Based on the results, reject rates were found to be lowest in curbside sort programs (0.4%), whereas the highest reject rates were in SSR collection programs (3.7%). In curbside programs, the material collector has a chance to leave rejects in the collection bin to show residents which recyclables are not accepted in the program, which helps to decrease the number of rejects.

The studies mentioned above analyzed the effect of SSR on MRFs processes, and also highlighted the significant impact that SSR has on paper mills and paper making processes. Sacia and Simmons (2005) examined the NORPAC paper mill in Longview, Washington to analyze and measure the impacts of residuals in paper bales from MRFs on the paper mill. Prior to 2001, all of the mill's incoming feedstock was from 100% source-separated programs and an additional 2,500 tons of fiber were required to replace the rejects (Morawski, 2010). Approximately 42% of incoming secondary newsprint came from commingled (single or dual stream) programs between 2003 and 2005. In these years, pulper rejects increased as the amount of feedstock collected from SSR programs increased.

Change in feedstock increased the need for replacement fiber by approximately 20,000 tons per year, which led to a $2 million per year increase in the mill's annual cost base for replacement fiber and disposal. Table 2 shows the changes in outthrows (all other paper grades that are not suitable to be in the production of a specific paper grade), prohibitive materials (materials that might make the product unusable depending on the requirements of that specific grade of paper or the potential for damage to the paper mill equipment), glass rate, and pulper yield loss for each period. While the difference in glass rates between different feedstock sources was negligible, the amount of outthrows, prohibitive materials, and pulper yield loss increased significantly with the increasing amount of feedstock collected from SSR. While the amount of prohibitive materials in the incoming stream is low, the materials can damage and degrade the quality of recycled paper. After 2004, the NORPAC paper mill made an investment of more than $100K to improve the quality of incoming material (Morawski, 2010).

TABLE 2. Effects of single stream on a paper mill (Morawski, 2010).

Time period	Feedstock source (as percent of the incoming material)	Outthrows	Prohibitive materials	Glass rate	Pulper yield loss
2001 and prior	Curbside sort (100%)	0.25% - 0.5%	0.0	0.0	1%
2003-2005	Single or dual 42%	5.7%	1.3%	0.1%	9%
Sep.-Dec. 2006	Single or dual 68%	15%	3.4%	0.33%	N/A

MWR facilities are also in the analysis, despite the limited number of paper mills that purchase recycled paper from these facilities. In an online survey conducted by ISRI (2016), researchers gauged the perceptions of representatives who buy and sell recovered fiber for United States paper mills. Of the 41 respondents, 25% purchase paper from mixed waste processing facilities. According to 70% of the respondents buying mixed waste paper, the quality of paper purchased from mixed waste facilities was found to be lower than other recovered paper. The survey found that contamination was one of the most important factors preventing respondents from buying recovered paper from mixed waste facilities (ISRI, 2016).

Waste collectors and local municipalities are generally happy with SSR because of the higher amount of recyclables collected, higher diversion rates, lower workers' compensation costs, fewer trucks on the road, and a wider range of materials in the stream. However, recovered material users see SSR as problematic because of poor quality recovered materials and higher internal costs due to high contamination (Jamelske and Kipperberg, 2006). While the studies conducted so far provide insight into how SSR affects contamination rates in MRFs and paper mills, more detailed studies are still needed to better understand the effect of SSR on paper contamination. To the best of our knowledge, there is no study that analyzes the effect of contamination on MRFs and paper mills in Florida. As mentioned earlier, the behavior of communities, the design of MRFs and paper mills, the demographic and geographic characteristics of the households, and current technology play important roles. There is a lack of research which would provide policy makers with more information on contamination rates and reveal the true expense of SSR for the counties in Florida. This study attempted to broaden the needed research to include paper contamination in MRFs and paper mills in Florida.

3 MATERIAL RECOVERY FACILITIES

Material recovery facilities (MRF) play a vital role in the integrated solid waste management system. In addition to understanding the way they operate, the latest developments in their activities, and the challenges that they face are all important aspects in establishing an effective solid waste management system. MRFs receive recyclable materials from different types of waste collection systems and then sort and prepare them for the end-users of the recovered materials. For example, they send paper bales to paper mills in the paper recycling process as shown in Figure 6. To the extent of our study, MRFs are explained under four collection categories as follows (Kessler Consulting, 2009):

- **Source separated:** Incoming recyclables are sorted by type at the point of collection. The primary purpose of the facility is to remove contaminants, often by baling, flattening, or crushing prior to sending them to market.
- **Dual stream:** Recovered materials are received in two separate streams, usually fiber (newspaper, magazines and catalogs, mixed paper, cardboard, etc.) and commingled containers (plastic, glass, metal, and sometimes aseptic containers). A combination of automated equipment and manual sorting are used for separation.
- **Single stream:** Fiber and commingled containers are received in a single stream. In the first stages of processing, materials are separated into two streams (fiber and containers). The rest of the processes are similar to that of dual stream.
- **Mixed waste:** Un-segregated mixed waste is received and separated using various technologies. Collected waste is first dumped onto a tipping floor and recyclable materials are then processed using equipment similar to a single stream MRF. Only 1% of residents with single-family curbside recycling programs in the United States have mixed waste collection systems (RRS, 2016).

Each collection system has advantages and disadvantages. For example, SSR makes the separation in MRFs more difficult and increases the cost of sorting and separation due to increasing contamination in the incoming waste stream. The average residual level in DSR is 6.79% (with glass); 11.71% (with glass) in SSR; and as high as 25-75% in MWR (Kessler Consulting Inc., 2009). The advantages and disadvantages of each collection system are given in Table 3.

TABLE 3. Advantages and disadvantages of waste collection systems.

Collection System	Advantages	Disadvantages
Source separated and dual stream (compared to other options)	• Increased quality of recovered products • Lower capital cost • Less operating costs	• Increased dependence on public participation • Increased collection costs • More waste collection vehicles
Single stream (compared to source separated and dual)	• Increased participation • Reduced collection costs • Less sorting effort for households • Fewer waste collection vehicles	• Increased processing costs of MRFs • Increased risk of cross contamination • Increased “down-cycling” of paper • Dissatisfaction of paper mills
Mixed waste (compared to other options)	• Low collection costs • No need for public participation • Fewer waste collection vehicles	• Higher capital and operating costs • Higher contamination • Lower recovery rates

While the major processing steps in MRFs are common for each recycling system, the design of the processing lines indicates some differences based on types of the materials to be processed, the desired quality of the end product, etc. The collected recyclables follow the processing line in a typical MRF as illustrated in Figure 11. *Tipping Floor (1)* is where trucks deliver mixed recyclables to the MRF; *Drum Feeder (2)* is where a claw gets material from the tipping floor and throws material into a spinning drum to distribute it evenly on a conveyor; *Initial Sorters (3)* is where workers remove items that might jam up the line; *Large Star Screens (4)* is where a series of star-shaped discs extract corrugated cardboard; *Second Sorters (5)* is where workers remove smaller contaminants; *Medium Star Screens (6)* is where smaller star screens lift out paper; *Glass Sorter (7)* is where glass, being heavier than aluminum and plastic, falls through the star screens and lands in bins below; *Magnetic Metal Sorter (8)* is where a magnet passes above the conveyor and attracts anything magnetic; *Eddy Current Separator (9)* is where a magnetic field induces electrons in aluminum and the eddy field pushes aluminum off the main conveyor onto another one; *Infrared Lasers (10)* is where laser beams target the remaining plastic items and a sensor detects the signatures of different grades of plastic; and *Baler (11)* is where the last machine on the conveyor makes piles of recycled paper, plastic, cardboard, or metal.

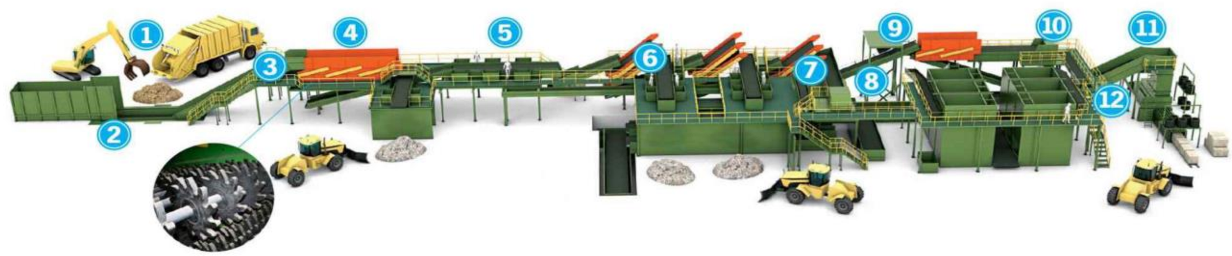

FIGURE 11. A typical SSR MRF process, courtesy of (Peek, 2013).

Each type of MRF has different additional steps and process lines to sort and recover waste streams with different compositions. As a result, they have different costs, as shown in the Pressley et al. (2015) study. Figure 12 shows that the total cost of SSR is higher than the other three MRF types. Lakhan (2015)'s study claims that there could possibly be a correlation between the quantity of recyclable material generated and the processing costs of MRF. For instance, in densely populated urban areas, processing costs of SSR MRFs are lower due to the large quantities of recyclables (Lakhan, 2015).

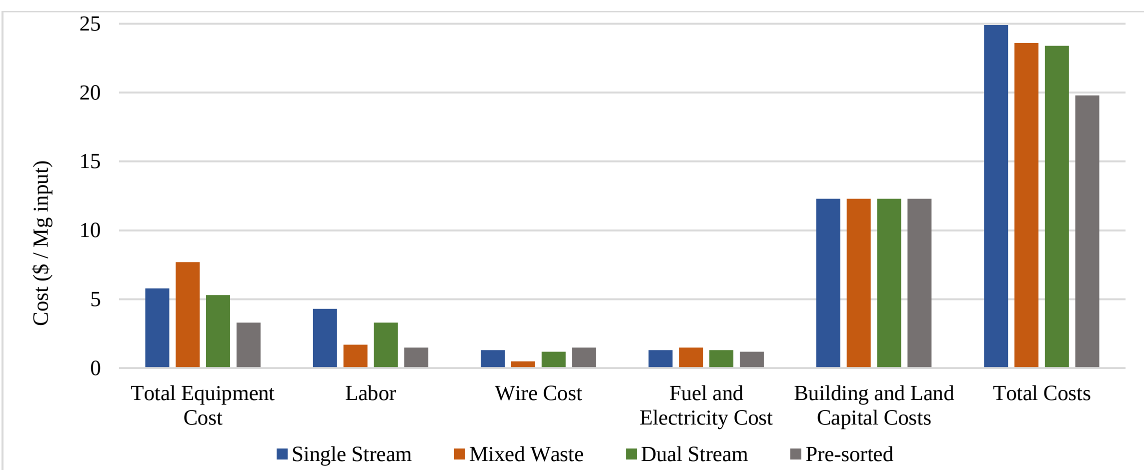

FIGURE 12. Cost summary by MRF type (Pressley et al., 2015).

Single stream MRFs are capable of recovering fiber, glass, metal and plastic from a commingled recyclables stream with the appropriate equipment and design. As this study focuses on paper contamination, we provide the process flow utilized for paper recycling. Based on our literature review (Kessler Consulting Inc., 2009; Combs, 2011; Pressley et al., 2015) and synthesis of our discussions with the counties in Florida, we developed a typical single stream MRF design for paper recycling, presented in Figure 13. The collection truck unloads the collected recyclables on the tipping floor and a claw pushes the material into the drum feeder. The drum feeder distributes the collected material to the conveyor where large items and prohibitive materials that can damage downstream equipment are removed by manual sorting. During manual sorting, plastic film (e.g., plastic bags) is also removed. Then, the remaining recyclables continue to Disc Screen 1, which separates the OCC, and the remaining mass travels to Disc Screen 2, which removes newsprint. The remaining material from Screen 2 continues to the Scalping Screen, which separates fiber from containers and other materials. The fiber streams from Disc Screen 2 and the Scalping Screen proceed to a manual sort to remove contaminants before the bailing process. After the bailing process, paper bales are sent to paper mills and processors.

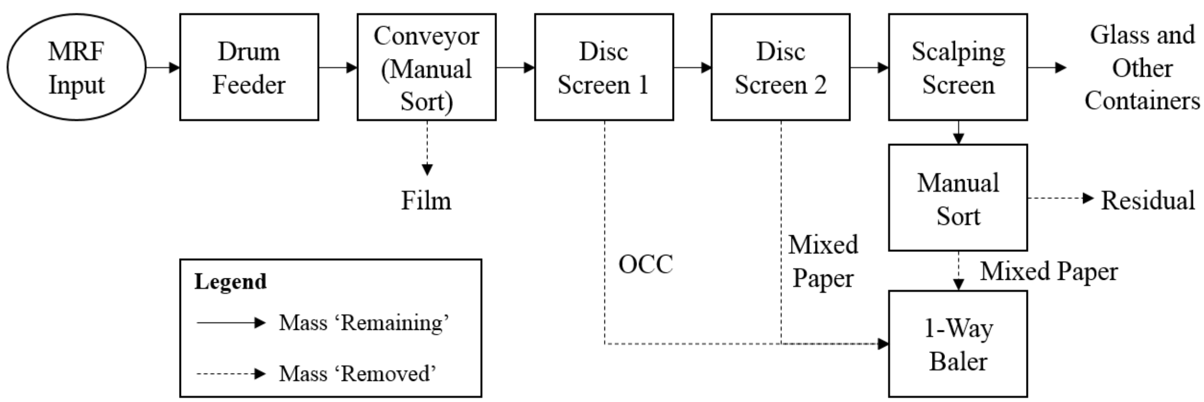

FIGURE 13. Single stream MRF process flow for paper recovery.

Designing material processing systems in MRFs is a challenging task because of the variability of feedstock, increased contaminants in the waste stream, and increasing pressure towards efficiency to reduce the long payback periods of high investments (Wolf et al., 2013). The design of a successful MRF should take several issues into account, including but not limited to, the most recent developments in processing technologies, composition of incoming materials, minimum required quality for the recovered materials, worker safety, environmental friendliness of the process, and flexibility to keep up with any potential changes in the waste stream. Efficiency - the ability of a MRF to correctly sort the material into proper streams - is an important measure of system performance. It can be calculated with the following equation:

$$Efficiency\ rate = \frac{Amount\ of\ material\ correctly\ sorted}{Total\ amount\ of\ material\ sorted\ in\ system}$$

The sorting efficiency has a direct impact on contamination rates. Improperly sorted recyclables become contaminants in other recyclable material streams or are sent to the landfill instead of being recovered. Analyzing inbound material composition (tip floor composition) and outbound material composition (bunker composition) and comparing them is a way to understand the overall system efficiency. However, efficiency in each and every step should be measured to determine where the system fails to sort the material properly and how this affects the efficiency of later phases. In order to achieve a higher system performance, process efficiency in each step should be maximized so that improperly sorted materials in earlier steps do not accumulate in later steps. When sorting at a MRF is inefficient, recovered material is contaminated. Paper processors and mills encounter quality issues, equipment damage, and high paper processing costs because of high contamination levels from SSR. Different sorting technologies may be implemented in MRFs to reduce contamination and maximize sorting efficiency. Processing equipment and systems are designed to sort recyclables based on different material characteristics: size, shape, weight, color, magnetic properties, etc. (The Dougherty Group LLC, 2006). Several methods are used on the conveyor lines to level material flow and increase the sorting efficiency. The materials can be fed onto a conveyor slowly to spread them out; a series of conveyor belts with gradually increasing speeds can be utilized for a more even flow of materials, a metering drum that rotates in the opposite direction to the materials can level out the material, or gates and curtains can be placed at specified heights above the inclined conveyor to allocate the aggregated materials over the conveyor (The Dougherty Group LLC, 2006). The most commonly used method to sort paper into various grades is disc screens. Multiple disc screens can be placed to sort different paper grades, one after another, as they flow. Usually, the first disc screen has wider spaces between the conveyors and discs to allow the flow of larger materials such as the OCC to move up the screen, and the newsprint is separated from mixed paper at the second disc screen with smaller spaces.

4 RECOVERED PAPER QUALITY

Despite the advanced design of MRFs to handle the non-recyclable materials, operations at MRFs are hindered by those unwanted items found within recyclable materials. High contamination in the incoming stream at paper mills causes not only additional sorting, processing, energy consumption, and higher costs, but also results in poorer quality recyclables and increased rejection and landfilling of unusable materials (FDEP, 2015). Based on the grade of the recovered paper, unwanted materials mixed in with the recyclable paper are defined under two categories: outthrows and prohibitive materials (American Recycling, 2011).

Similarly, prohibitive materials might make the product unusable depending on the requirements of that specific grade of paper, and they can also damage paper mill equipment. Cans, bottles, glass, plastic bags, and metals are examples of prohibitive materials (Rock Tenn, 2011). Prohibitive materials can also be referred to as cross contamination, where the paper is contaminated by the other recyclables in the stream, such as broken glass. Although the glass can be recycled indefinitely, in SSR collection it might contaminate paper. Glass pieces smaller than 3/8" (resulting from breakage during collection and transportation) can mix with paper (FDEP, 2015), and can damage MRF equipment and lower fiber quality in paper mills.

Outthrows are defined as all other paper grades that are not suitable in the production of a specific paper grade. The quality of recovered paper is improved by removing contaminants. Excessive amounts of outthrows or prohibitive materials leads to downgrading of the paper. The limit of the contaminants in each grade of paper varies among different paper mills and end-users. The Institute of Scrap Recycling Industries, Inc. (ISRI) provides guidelines for maximum acceptable prohibitive materials and outthrows, based on the recovered paper grade, as shown in Table 4.

TABLE 4. Allowable limits of prohibitive materials and outthrows for paper grades (ISRI, 2013).

Type of the paper	Prohibitive materials limit	Outthrows plus prohibitive materials limit	Type of the paper	Prohibitive materials limit	Outthrows plus prohibitive materials limit
Residential Mixed Paper	2%	5%	Coated Flyleaf Shavings	None permitted	1%
Soft Mixed Paper	1%	5%	Coated Soft White Shavings (SWS)	None permitted	1%
Hard Mixed Paper (HMP)	½ of 1%	3%	Hard White Shavings (HWS)	None permitted	½ of 1%
Boxboard Cuttings	½ of 1%	2%	Hard White Envelope Cuttings	None permitted	½ of 1%
Mill Wrappers	½ of 1%	3%	New Colored Envelope Cuttings	None permitted	2%
Old Newspaper	2%	4%	Semi Bleached Cuttings	None permitted	2%
Regular News, De-ink Quality	1%	3%	Unsorted Office Paper (UOP)	2%	10%
Special News, De-ink Quality	1%	2%	Sorted Office Paper (SOP)	1%	5%
Over-Issue News (OI or OIN)	None permitted	None permitted	Manifold Colored Ledger (MCL)	½ of 1%	2%
Magazines (OMG)	1%	3%	Sorted White Ledger (SWL)	½ of 1%	2%
Old Corrugated Containers (OCC)	1%	5%	Manifold White Ledger (MWL)	½ of 1%	2%
Double-Sorted Old Corrugated	½ of 1%	2%	Coated Book Stock (CBS)	None permitted	2%
New Double-Lined Kraft Corrugated Cuttings (DLK)	None permitted	2%	Coated Ground wood Sections (CGS)	None permitted	2%
Fiber Cores	1%	5%	Printed Bleached Board	1%	2%
Used Brown Kraft	None permitted	½ of 1%	Unprinted Bleached Board	None permitted	1%
Mixed Kraft Cuttings	None permitted	1%	#1 Bleached Cup Stock (#1 Cup)	None permitted	1%
Carrier Stock	None permitted	1%	#2 Printed Bleached Cup Stock (#2 Cup)	None permitted	1%
New Colored Kraft	None permitted	1%	Unprinted Bleached Plate Stock	None permitted	½ of 1%
Kraft Grocery Bag (KGB)	None permitted	1%	Printed Bleached Plate Stock	None permitted	1%
New Kraft Multi-Wall Bag	None permitted	1%	Aseptic Packaging and Gable-Top	2%	5%

			Cartons		
New Brown Kraft Envelope Cuttings	None permitted	1%	White Blank News (WBN)	None permitted	1%
Mixed Flyleaf Shavings	None permitted	2%	Ground wood Computer Printout (GW CPO)	None permitted	2%
Telephone Directories	None permitted	½ of 1%	Publication Blanks (CPB)	None permitted	1%

Paper can also be contaminated by the products that are used to prepare it for sale, such as printed inks, adhesives, and polyethylene or foil liners, as well as by the non-fibrous materials that enter the recovered paper stream, such as staples, rubber bands, and food debris (McKinney, 1995). These materials are unacceptable contaminants and might pose a health and safety risk for workers and consumers. Most of the recycling mills make use of deinking which combines processes that remove the inks, laser and copier toner, and contaminants such as labels, glues, plastic windows, paper clips and other materials (Conservatree, 2016).

Other than the deinking process, recovered paper goes through different pre-processes in paper mills before it is used in paper production. In the first stage of pulp production, recovered fibers from newspapers and magazines are mixed with a fatty acid soap solution, and large volumes of warm water are rotated with the mixture in a large pulping vessel to break down the bonds between the fibers (SCA, 2010). The deinking process starts by relaxing the bonds of the ink from the fibers. During this process, most of the heavy undesirable materials such as binding staples, CD cases, plastic wrapping, and other foreign objects are sorted out of the paper. Next, the ink is removed in a multi-stage washing process and the clean fiber is bleached, if necessary.

Another important factor that affects the recovered paper quality is the number of times the recovered paper is recycled before the current process. As opposed to indefinitely recoverable glass, paper fibers are shortened in the recycling process, and eventually, they become too short and cannot be recycled again. As the recovered paper quality is reduced, more raw materials are needed to maintain a minimum paper quality.

5 DATA COLLECTION AND ANALYSIS

Many municipalities have started to consider SSR as the sole way to reach state recycling goals, increase public's participation and the amount of materials collected, and reduce collection costs. The success of a new system depends on many variables, including public support and the utilization of advanced processes in MRFs, which is hard to measure. For instance, an increase in the amount of collected recyclables might hardly show success if the contamination rates are high and recyclable materials end up in landfills due to the unwanted materials in the stream. Increasing recycling tonnage and community participation are two important indicators to show how successful SSR is. However, they might mislead decision makers if contamination rates in the recovered material are too high and not taken into consideration. To this end, the purpose of this study is to identify if the recovered fiber materials are contaminated as the paper processing industry claims and evaluate if the SSR programs have a significant role in paper contamination. In this study, as a first step, researchers collected and collated data for inbound and outbound contamination rates in recyclables and in recovered paper collected by currently operating industrial facilities including MRFs and paper mills, counties, cities, and transfer stations in Florida.Recyclable material composition studies from 15 counties in Florida were also analyzed.

5.1 ANALYSIS OF INBOUND CONTAMINATION RATES

The first task of data collection was to bring together the recyclable composition studies conducted for the inbound waste stream in counties, cities, MRFs, and transfer stations in Florida. Recyclable composition studies were requested from 67 counties. Seminole, Leon, Pasco, Sarasota, Indian River, Brevard, Escambia, Santa Rosa, Hillsborough, Okaloosa, Lee, Marion, and Citrus counties provided composition studies, as did the municipalities of Fort Lauderdale, Margate, and Lauderdale by the Sea. The reports provided individual sample results showing the breakdown of recyclable materials, as well as the contamination rates. DSR data consisted of the contamination in the paper stream. The standard deviation (8.97) and mean (18.54) of the SSR contamination rates were higher than those of the DSR contamination rates (3.08 and 3.89, respectively). SSR contamination rates were more spread out over a wide range of values than were DSR contamination rates. Any evident difference between the two groups was worthy of additional data analysis. Analysis of variance (ANOVA) was used to further investigate the difference between SSR and DSR contamination rates. ANOVA assumes that each group sample is taken from a normally distributed population. Histograms for the SSR and DSR contamination rates were plotted (Figure 14). It was indicated that further statistical tests needed to be conducted to test the normality of two groups of samples.

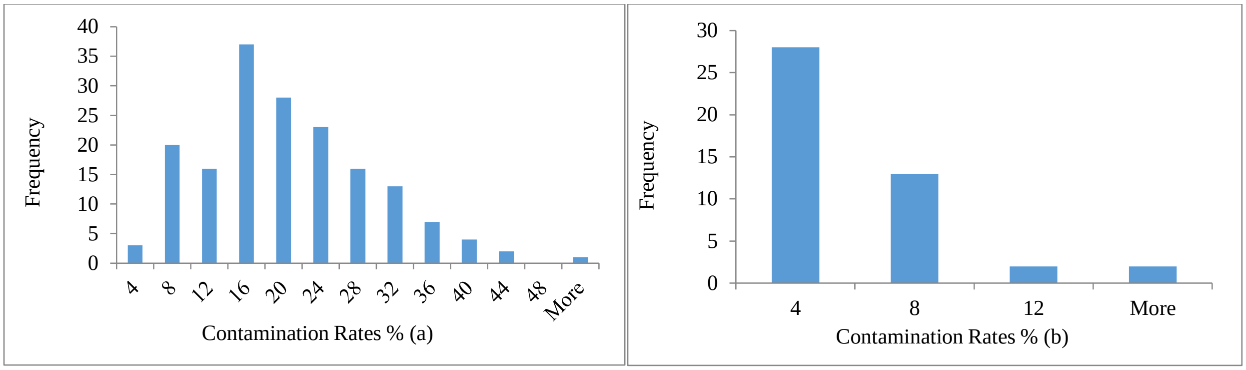

FIGURE 14. Histograms for samples from SSR (a) and DSR (b).

The Anderson-Darling (AD) normality test was used to test the normality assumption for ANOVA. AD is a non-parametric test that comes in handy when there are a limited number of samples available. It takes into consideration not only the means of samples but also differences in shape and variability of the distributions. Normality test plots and statistics for SSR and DSR are shown in Figure 15. Both samples comply with the normality assumption of ANOVA, based on AD normality test results.

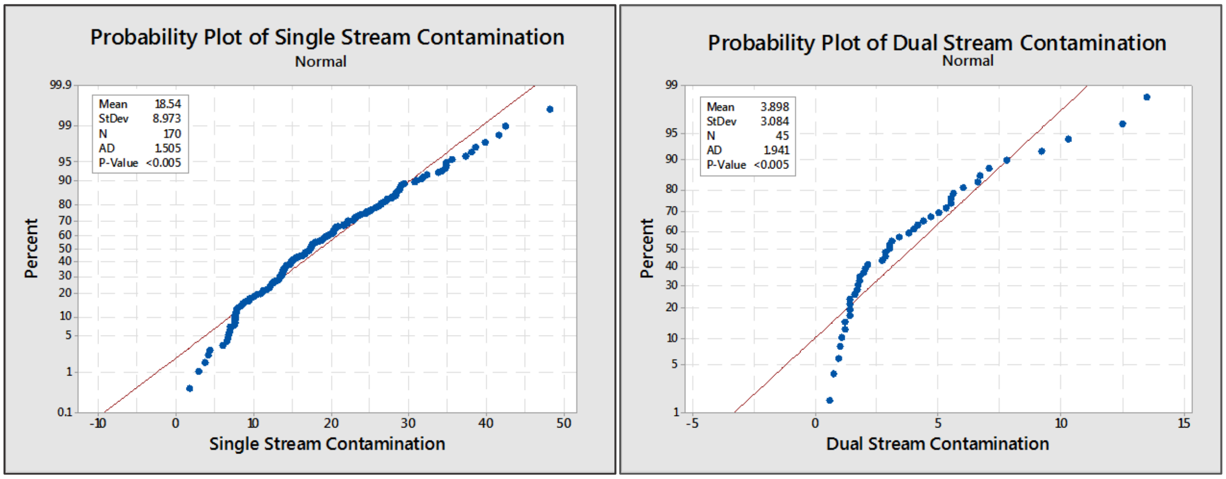

FIGURE 15. Anderson-Darling normality test results for single stream and dual stream samples.

Dealing with unequal sample sizes of SSR and DSR:

Exactly 215 samples were used in single factor ANOVA. Of the data points, 170 data points belonged to the SSR sampling results, whereas the other 45 data points belonged to the DSR sampling results, resulting in a dataset with unequal sample sizes. Firstly, the sample sizes were balanced by randomly selecting a sample from the SSR dataset using SPSS statistics software. After balancing, we had a random sample of SSR equal to 45 and a random sample of DSR equal to 45. Mean and standard deviation of the random sample from SSR were 18.94 and 8.98, respectively (see Figure 16).

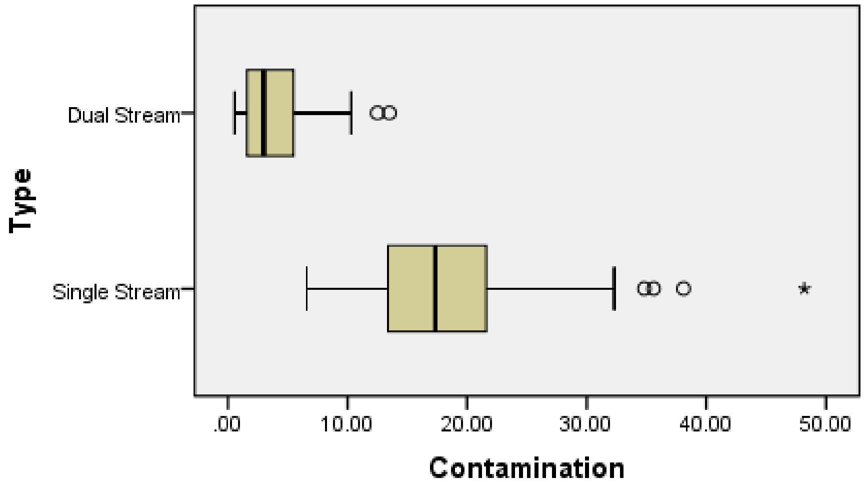

FIGURE 16. SSR and DSR data with equal sample sizes after random sampling.

The 95% confidence interval was also calculated for each recycling program (see Table 5). The confidence interval shows that, with a 95% level of confidence, the actual arithmetic mean of contamination rates were within the upper and lower limits shown in Table 5. The means of SSR and DSR contamination rates were within (16.2455 – 21.6425) and (2.9717 – 4.8247), respectively with 95% confidence. The interval for mean of SSR contamination rates was higher than that of DSR. Further analysis was conducted to understand if this difference was significant.

TABLE 5. Descriptive statistics of dataset after balancing sample sizes.

Statistics	**SSR**	**DSR**	**Total**
N	45	45	90
Mean	18.9440	3.8982	11.4211
Standard Deviation	8.98200	3.08381	10.09040
Standard Error	1.33896	0.45971	1.06362
95% Lower Bound	16.2455	2.9717	9.3077
95% Upper Bound	21.6425	4.8247	13.5345
Minimum Value	6.59	0.57	0.57
Maximum Value	48.20	13.50	48.20

<u>ANOVA:</u>

The next step was to conduct ANOVA. The purpose in ANOVA is to compare the ratio of between-group variance to within-group variance and the F critical ratio. ANOVA expressions are shown in Table 6. Additional information about ANOVA is provided in Appendix B. Between-group variation and within-group variation are denoted by SS_B and SS_W, respectively. SS_T is the sum of SS_W and SS_T. K is the number of levels and N is the number of observations in each level.

TABLE 6. ANOVA formulas.

Source of variation	**Sum of squares**	**Degrees of freedom**	**Mean square**	**F ratio (test statistic)**
Between	SS_B	*K-1*	$MS_B = SS_B\ /\ (K-1)$	$MS_B\ /\ MS_W$
Within	SS_W	*N-K*	$MS_W = SS_W\ /\ (N-K)$	

Total	SS_T	*N-1*

The factor (independent variable) was the type of recycling program and the levels were utilizing SSR and utilizing DSR. The dependent variable in ANOVA was contamination rates in counties/cities that implement different recycling programs. The null hypothesis was "having equal contamination rates in SSR and DSR" while the alternative hypothesis was "having different contamination rates." Using F-ratio, the ANOVA tested if the means of different levels on the dependent variable were significantly different from each other. If the f ratio was smaller than the f critical ratio, then we cannot reject the null hypothesis. Otherwise, we can reject the null hypothesis and conclude that the contamination rates of SSR and DSR are significantly different from each other. ANOVA was performed using SPSS statistics software and the results are shown in Table 7. The p-value was smaller than 0.05, meaning the contamination rates of SSR and DSR were significantly different from each other with 0.05 significance level. The difference between SSR and DSR contamination rates was found to be statistically significant. In Section 5.2, contamination rates of three types of waste generators – single-family residential, multi-family residential, and commercial - are compared using ANOVA. Further analysis was conducted to understand the impact of high contamination rates in recycling rates in single stream programs. Adjusted recycling rates were computed and presented in Section 5.3.

TABLE 7. ANOVA to assess the impact of SSR on contamination rates.

Source of variation	**Sum of squares**	**Degrees of freedom**	**Mean square**	**F (test statistic)**	**P-value**
Between Groups	5093.447	1	5093.447	112.954	0.000
Within Groups	3968.194	88	45.093		
Total	9061.641	89			

5.2 ASSESSMENT OF WASTE GENERATOR SECTORS

In this section, waste generator sectors – single-family residential, multi-family residential and commercial - were analyzed in terms of the reject rates of the incoming stream. According to the data collected from waste composition studies, two similar counties in terms of their socio-economic characteristics, County 2 and County 7, were subject to this analysis. Particularly, County 2 and County 7 are middle-income counties with populations between 200,000 and 300,000. ANOVA was applied to assess if there was significant statistical evidence for the difference in reject rates among the three waste generator sectors.

<u>County 2 (Refer to Section 5.3):</u>

ANOVA and a multiple comparison test were implemented to analyze the rejects rates from three different waste generator sectors for County 2. The results of the analysis are presented in Table 8, and Figures 17 and 18.

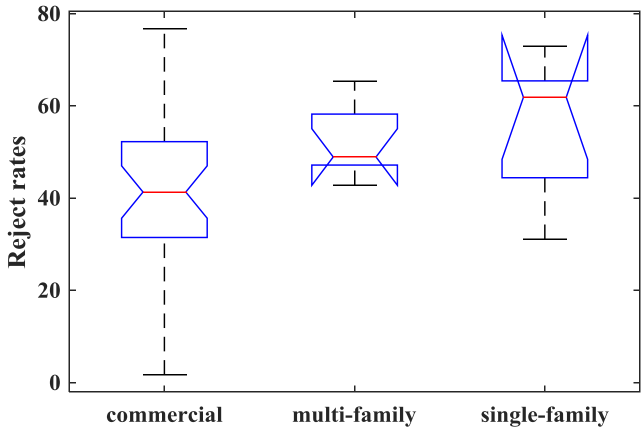

FIGURE 17. Box plot of reject rate for single-family, multi-family and commercial waste generator sectors.

Compared to other counties (see Section 5.1), the mean of the reject rates in County 2 was very high for all sectors. Based on the descriptive statistics, single-family residences generate the highest reject rates while the commercial sector has the lowest reject rate. The variance in reject rates for the commercial sector was higher than that of the other sectors. In the composition study, a university's waste stream was analyzed separately among others in the commercial sector. The average reject rate in the collected samples from the university was 38.3%. The high range for the commercial sector indicates the necessity for further analysis to determine the problematic commercials. ANOVA was conducted in order to test if the difference in means of reject rates for these three sectors is statistically significant.

TABLE 8. ANOVA to assess the impact of waste generator sectors on reject rates.

Source of variation	Sum of squares	Degrees of freedom	Mean square	F (test statistic)	P-value
Between Groups	1139.3	2	569.628	2.55	0.0897
Within Groups	9835.5	44	223.535		
Total	10974.8	46			

The analysis resulted in a p-value less than 0.1. The null hypothesis was rejected, which showed that at least one sector mean was different from the rest with 0.1 significance level. In order to analyze these groups in more detail, a multiple comparison test was further conducted. The test results are shown in Figure 18.

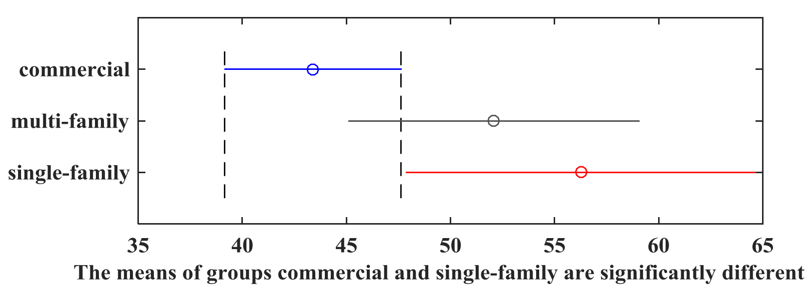

FIGURE 18. Result of multiple comparison test.

With 0.15 significance level, our multiple comparison test found that the means of commercial and single-family sectors were significantly different. Based on our analysis, County 2 could focus more on educating people in single-family residences. More importantly, there was significant difference between County 2 and other counties in terms of reject rates. While the average reject rate in the incoming stream was around 19% in other counties, the rate was around 50% in County 2. Another important observation in County 2 was about newspaper recycling. Newspapers constitute about 2-3% of total waste composition. According to FDEP data for 2013-2015, the recycling rate of newspapers was 0%. Before 2013, the recycling rate of newspapers was around 1-2%. In this case, newspapers might be one of the contaminants affecting recycling of other paper grades.

County 7 (Refer to Section 5.3):

The results of our analysis for County 7 are provided in Table 9 and Figures 19 and 20. As seen from Figure 17, the mean of the reject rates from the three sectors are between 11% and 17%. Unlike County 2, the mean of the reject rates in multi-family residences was higher than the mean in single-family residences and commercial businesses. The comparison between County 7 and County 2 showed that different counties have different characteristics and require different programs and incentives to decrease the reject rates. Then, we conducted ANOVA to further analyze the difference in means of reject rates for the three sectors.

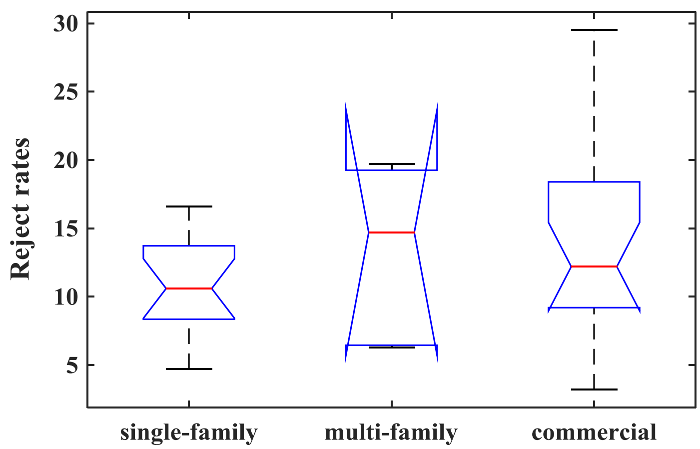

FIGURE 19. Box plot of reject rate for single-family, multi-family and commercial waste generator sectors.

TABLE 9. ANOVA to assess the impact of waste generator sectors on reject rates.

Source of variation	Sum of squares	Degrees of freedom	Mean square	F (test statistic)	P-value
Between Groups	61.93	2	30.9633	0.95	0.3944
Within Groups	1200.61	37	32.4489		
Total	1262.54	39			

The analysis resulted in a high p-value, almost 0.4. This means that there was no statistically significant evidence that showed the differences in means of reject rates in these three sectors. In order to analyze these groups in more detail, a multiple comparison test was further conducted. The test results are shown in Figure 20.

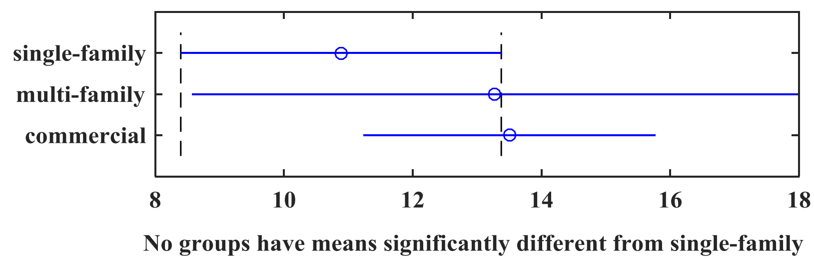

FIGURE 20. Result of multiple comparison test.

With the 0.1 significance level, no groups have means significantly different from each other. When the significance level was set to 0.4, found by ANOVA, the means of single-family and commercial were significantly different. While the results showed that the reject rates were equal for these three sectors, the descriptive statistics and box plot indicated that the multi-family sector was the most problematic waste generator sector in terms of reject rates. Educating the managers of multi-family residences or including some flyers on the containers in multi-family complexes can help reduce the reject and contamination rates in the incoming stream for paper recycling.

5.3 ASSESSMENT OF ADJUSTED RECYCLING RATES

The largest contamination rate among the counties that use SSR was 28.2% (County 1). The following observations were made regarding the samples collected from County 1:

- The main contributor of contamination was the large number of small plastic bags filled with MSW.
- A wide range of MSW from used diapers to food waste was improperly disposed of in SSR containers.
- There were also some items that people mistakenly thought are recyclables, such as shredded office paper, large plastic containers, aluminum foil, and some food containers.
- Paper products that are very soiled, saturated with water, or degraded were also one of the main contributors to contamination.

The recycling rate of County 1 was 58% in 2015. Assuming all recyclables collected from the counties were transferred to a SSR MRF to be processed, 28.2% of the total recyclables collected from County 1 was contaminated and disposed of in landfills, which leaves a recycling rate of 41.64% (58-58*28.2%) for the county. This simple calculation showed that just because SSR increases the amount of recyclables collected does not mean it will also increase recycling rates. Public outreach might have an important impact on reducing contamination rates.

The smallest contamination rate, on the other hand, was 7.5% (County 11). The recycling rate of County 11 was 35% in 2015. Taking contamination out of the recycling rate left a recycling rate of 32.37% for County 11. Taking contamination rates into consideration to compute recycling rates lowered the percent difference between County 1 and County 11 from 23% (58% – 35%) to 9.27% (41.64 – 32.37%). The way the recycling rates were calculated can be very misleading when the contamination rates are high. This might mislead decision makers to mistakenly give counties credit for higher recycling rates, which can affect projects designed to improve recycling rates. Average contamination rates, along with recycling rates (with and without taking contamination rates into consideration) for the 15 counties are presented in Table 10. Adjusted recycling rates were calculated based on the assumption that all recyclables collected were transferred to a SSR MRF for processing.

TABLE 10. Calculation of recycling rates after contamination for counties with SSR.

County Largest to Smallest	Recycling Rate	Contamination Rate	Adjusted Recycling Rate
1	**58%**	**28.2%**	**41.64%**
2	51%	7.7%	47.07%
3	51%	7.6%	47.12%
4	49%	20%	39.20%
5	47%	7.6%	43.43%
6	46%	14.1%	39.51%
7	43%	12%	37.84%
8	43%	19.8%	34.49%
9	43%	16%	36.12%
10	39%	18.8%	31.67%
11	**35%**	**7.5%**	**32.37%**
12	34%	10.4%	30.46%
13	24%	13%	20.88%

County 1 had the largest reported recycling rate. After its recycling rate was adjusted by subtracting its contamination rate from its reported recycling rate, its recycling rate was ranked as the fourth-largest recycling rate among the counties. Figure 21 gives a better picture of adjusted recycling rates. This analysis provides insight about how the inbound contamination rates in SSR affect the actual recycling rates. Contamination left in the recovered material at MRFs should also be analyzed to get a clear picture of contamination during the entire flow of recyclable material in SSR systems.

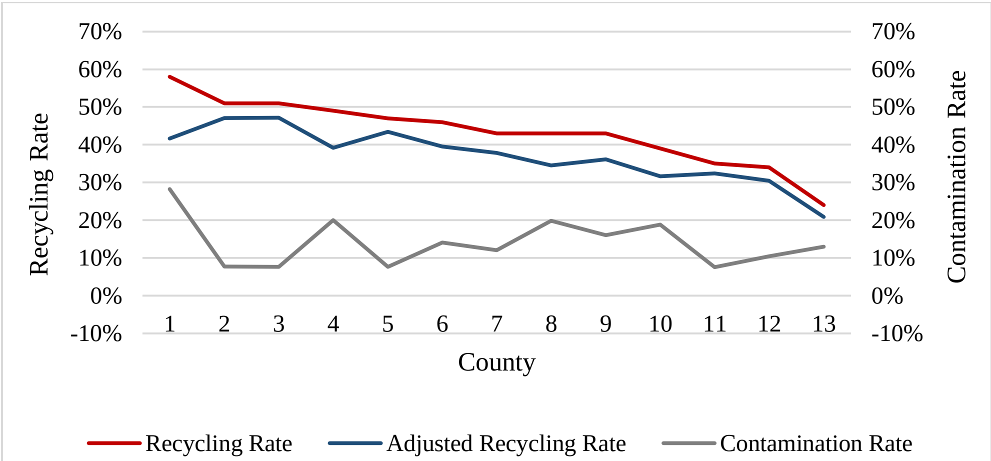

FIGURE 21. Adjusted recycling rates for counties that utilize SSR.

5.4 ANALYSIS OF OUTBOUND CONTAMINATION RATES

Outbound contamination rates in recovered old corrugated containers (OCC) and old newsprint (ONP) bales were obtained from six operating facilities in Florida. In order to maintain consistency in data, the data from four of them were used in this analysis. In the dataset, the weight of each material was reported. Average rates of acceptable recovered material, brown paper, outthrows, and prohibitive materials in 266 samples from the ONP stream were 67.41%, 7.81%, 17.66%, and 7.13% respectively (see Figure 22). Average rates of acceptable recovered material, outthrows, and prohibitive materials in 35 samples from the OCC stream were 91.12%, 3.75%, and 5.12%, respectively. For example, if 100 tons of ONP are received by the paper mill, the weight of acceptable ONP would be only 67 tons, on average. If 100 tons of the OCC is received by the paper mill, the weight of acceptable OCC would be 91 tons, on average.

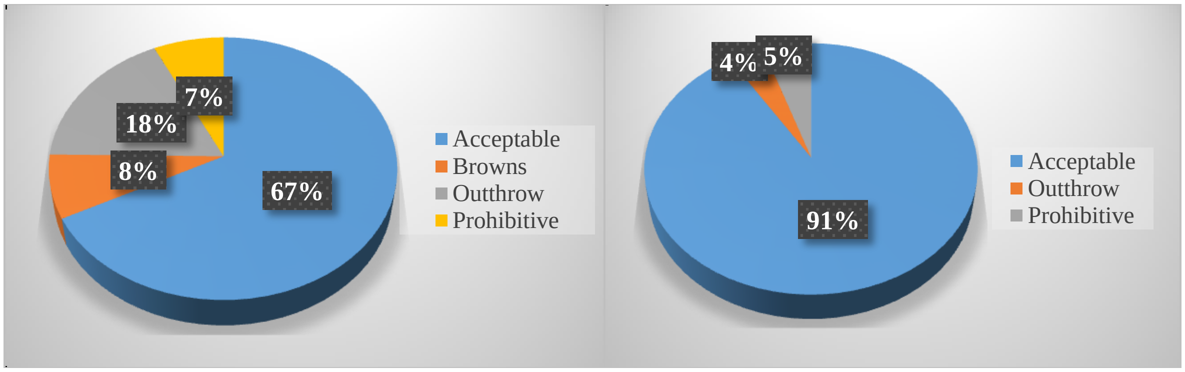

FIGURE 22. Aggregated analysis of the ONP (left) and the OCC (right) samples.

Rates of different types of contamination (brown paper, prohibitive materials, and outthrows) were also analyzed in randomly selected samples from the ONP and the OCC streams. Figure 23 shows the brown paper, outthrows, and prohibitive material rates for 50 samples from the ONP stream, and outthrows and prohibitive material rates for 35 samples from the OCC stream. Mean prohibitive material rates in the OCC, mean rates of outthrows in the ONP, and mean prohibitive material rates in the ONP were higher than the maximum contaminant level allowed by the paper mills. Contamination rates of a great majority of samples were above the maximum allowable limit set by the paper mills. Mean rates of outthrows in the OCC and brown paper rates in the ONP were lower than the maximum allowable limits at the paper mills. However, some of the samples still had a higher contamination rate than the paper mill standards.

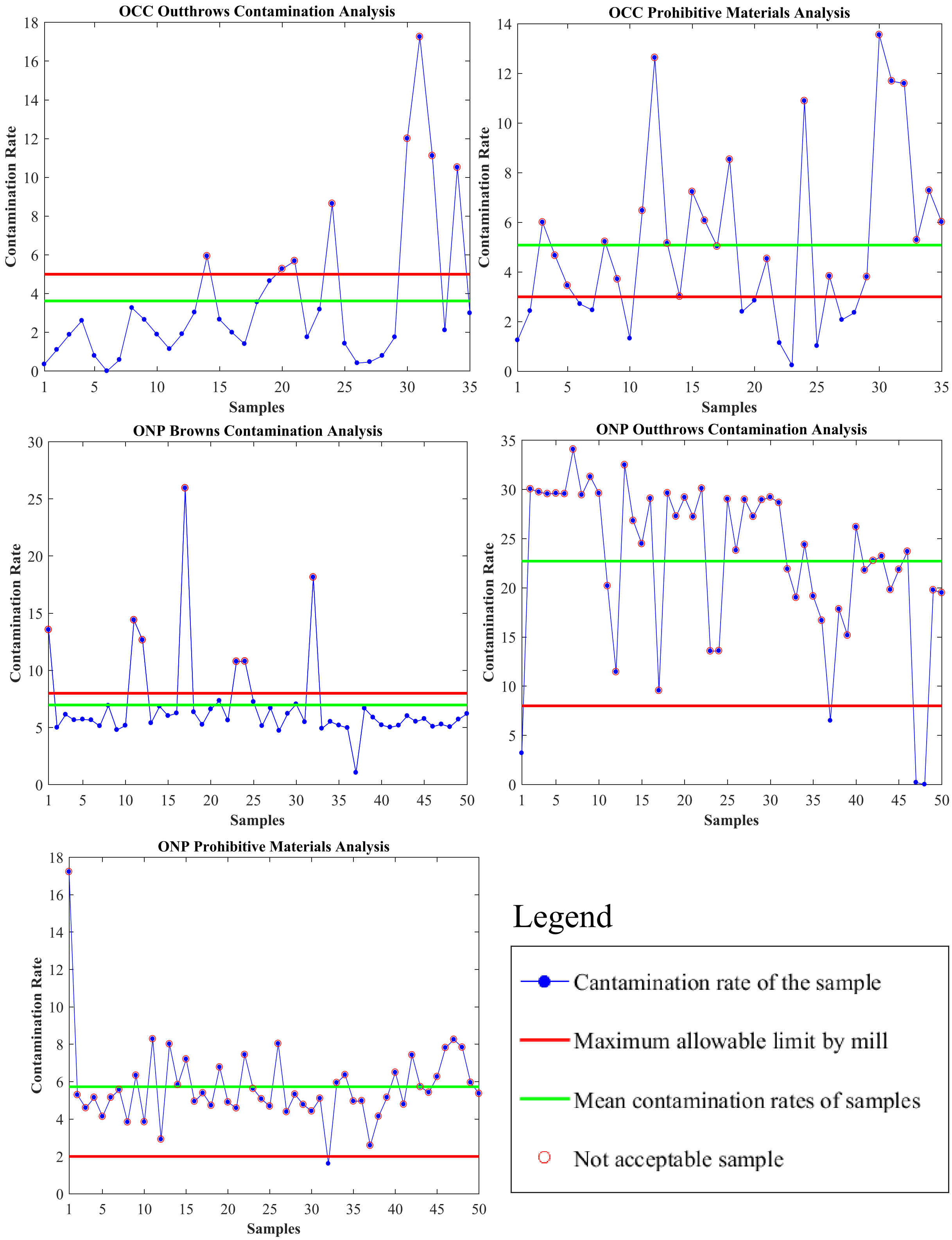

FIGURE 23. Outbound contamination rates in the ONP and the OCC recovered paper streams.

We analyzed all three types of contamination to determine whether they were higher or lower than the allowable paper mill limits for each of the ONP and OCC samples. The Venn diagrams in Figure 24 demonstrate what percentage of the OCC samples passed the allowable limits for outthrows only (2.9%), prohibitive materials only (20%), outthrows and prohibitive materials (45.7%), and what percentage of the ONP samples passed the allowable limits for brown paper only (0%), outthrows only (0%), prohibitive materials only (4.9%), brown and outthrows (0.4%), brown and prohibitive materials (5.3%), outthrows and prohibitive materials (73.7%), and brown, outthrows, and prohibitive materials (16.8%). 31.4% of the OCC samples had lower contamination rates than the allowable limits for both outthrows and prohibitive materials. All samples in the ONP stream had dramatically higher contamination rates than allowable limits for at least one of the contamination types (brown paper, outthrows, or prohibitive materials).

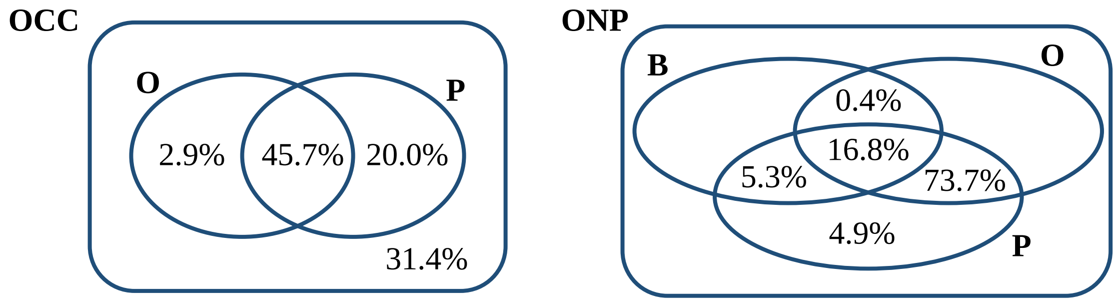

FIGURE 24. Percentage of samples that passed the allowable limits of outthrows (O), prohibitive materials (P), and brown paper (B).

Sub material analysis was performed to reveal the most problematic types of prohibitive materials and outthrows in the ONP and the OCC streams. The great majority (68%) of prohibitive materials in the OCC stream was made up of residues (Figure 25). MRF film plastic (9%) was the next major prohibitive material type in the stream. This analysis supports the claim by paper mills that plastic films are one of the most common prohibitive materials. The great majority of outthrows in the OCC stream were ONP8 (51%) and mixed paper (36%).

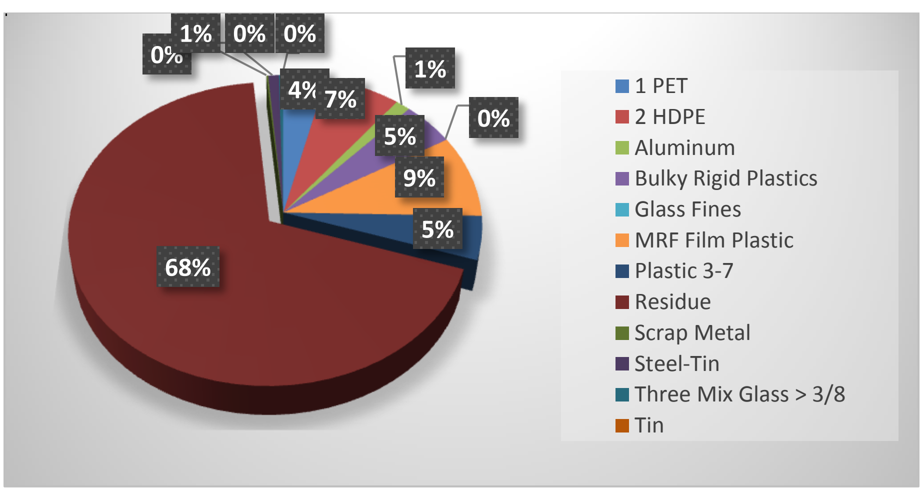

FIGURE 25. Prohibitive material analysis in the OCC material stream.

The great majority of prohibitive materials in the ONP material stream were residue (57%), PET (14%), and MRF film plastic (8%) (Figure 26).

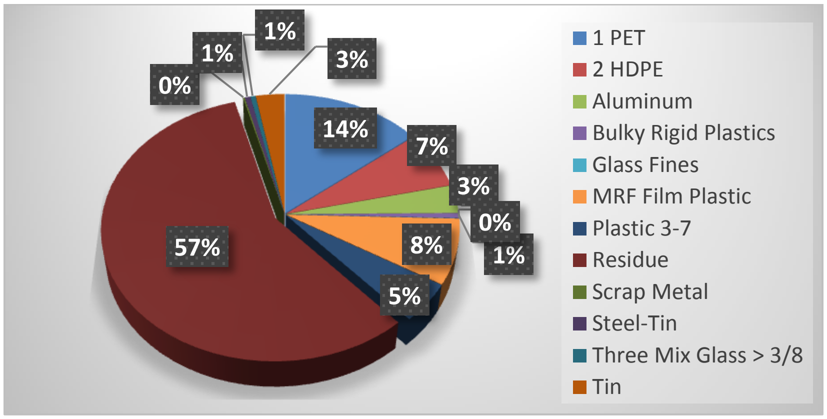

FIGURE 26. Prohibitive material analysis in the ONP material stream.

6 CONCLUSION

This study was conducted to analyze the impact of single stream recycling (SSR) on contamination rates in Florida's recyclable paper stream. Researchers requested the contamination rates in recyclables from 67 Florida counties. Material composition studies were obtained from Seminole, Leon, Pasco, Sarasota, Indian River, Brevard, Escambia, Santa Rosa, Hillsborough, Okaloosa, Lee, Marion, and Citrus counties, and also from three municipalities: Fort Lauderdale, Margate, and Lauderdale by the Sea. The standard deviation (8.97) and mean (18.54) contamination rates of the samples from SSR were higher than the samples from DSR. (3.08 and 3.89, respectively). Analysis of variance (ANOVA) was conducted to determine the difference in contamination rates. The difference between SSR and DSR inbound contamination rates was found to be statistically significant.

Further analysis was conducted for two comparable SSR counties (County 2 and 7) to determine if the inbound contamination rates for different waste generator sectors (single-family, multi-family, and commercial) were different. In County 2, single-family residences generate the highest reject rates, while commercial has the lowest reject rate. County 2 should focus on educating single-family residents as to which materials can go to single stream bins. On the other hand, the reject rates of single-family, multi-family, and commercial sectors for County 7 were not statistically significantly different from each other based on ANOVA results. The mean reject rates were the highest in the multi-family sector. Therefore, educating the managers of multi-family complexes or including flyers on the recycling containers are viable options to help reduce the reject rates in the SSR incoming stream.

In order to better understand the impact of single stream collection on paper recycling rates, further analysis was conducted in three counties. Brevard (2009), Broward (2009), and Miami-Dade (2008) were among the counties that converted to SSR during 2008-2009. Two-factor multivariate analysis of variance (MANOVA) was used to understand if the recycling rates before and after the counties switched to SSR were statistically different from each other. Table 11 shows the recycling rates of these counties during 2000-2015.

TABLE 11. Change in paper recycling rates of counties which switched to SSR: Broward, Miami-Dade, and Brevard.

Year	Newspaper			Other Paper		
	Brevard	Broward	Miami-Dade	Brevard	Broward	Miami-Dade
2000	7%	4%	5%	23%	21%	27%
2001	6%	6%	5%	21%	22%	25%
2002	9%	6%	5%	19%	22%	27%
2003	3%	5%	6%	13%	22%	26%
2004	3%	6%	5%	13%	21%	26%
2005	4%	5%	5%	13%	19%	23%
2006	2%	4%	5%	16%	19%	25%
2007	2%	4%	5%	19%	20%	25%
2008	2%	5%	5%	19%	22%	25%
2009	2%	6%	5%	18%	22%	24%
2010	3%	6%	5%	18%	23%	26%
2011	3%	5%	5%	18%	21%	26%
2012	51%	30%	25%	33%	32%	26%
2013	28%	26%	19%	14%	36%	21%
2014	47%	13%	12%	16%	27%	20%
2015	19%	11%	8%	22%	42%	15%

The p-value for Wilks' Lambda statistic was 0.087 ($p > 0.05$) for Brevard County. Based on the MANOVA results (see Appendix C for MANOVA plots), there was not a statistically significant difference between the recycling rates before and after Brevard county switched to SSR. The p-values for Wilks' Lambda statistic were 0.008 and 0.032 ($p < 0.05$) for Broward County and Miami-Dade, respectively. Based on the MANOVA results, there was a statistically significant difference between the recycling rates before and after Broward and Miami-Dade switched to SSR. There might be several reasons behind this difference. Brevard County's population is around 550,000, while the population of Broward and Miami-Dade Counties is around 1.8 million and 2.6 million, respectively. Another reason might be the number of tourists who visit the counties. Broward County (6.4% of total visitors to Florida) and Miami-Dade County (5.9% of total visitors to Florida) were ranked in the top 10 most-visited counties, based on 2010 statistics (Florida Department of Transportation, 2012). As the potential for recycling increases due to high population and higher numbers of visitors, the impact of SSR on recycling rates might be increasing as well.

As for the outbound contamination aspect, the acceptable OCC and ONP rates were 91.12% and 67.41% of the total weight on average for all samples. Average rates (weight of the contamination/total sample weight) of brown paper, outthrows, and prohibitive materials in 266 samples from the ONP stream were 7.81%, 17.66%, and 7.13% respectively. Among 266 samples from the ONP stream, none of the samples could pass the paper mill standards due to the high rates of at least one of the contamination types (brown paper, outthrows, or prohibitive materials). Average rates of outthrows and prohibitive materials in 35 samples from the OCC stream were 3.75%, and 5.12%, respectively. Among 35 samples from the OCC stream, only 31.4% of samples had lower contamination rates than the maximum allowed by paper mills for both outthrows and prohibitive materials. The most common types of prohibitive materials in the OCC and ONP streams were residue, MRF film plastic, high-density HDPE and PET.

This study provides a comprehensive analysis on the effect of SSR on incoming contamination. Our results indicate that there is strong evidence that SSR increases the incoming contamination compared to DSR. Waste generator sectors were then analyzed to guide counties in determining which communities to target in the effort to decrease contamination rates. An adjusted recycling rate measure has been developed to monitor the current situation more accurately. Lastly, the newspaper and other paper recycling rates were analyzed after the three counties switched to SSR from DSR. The results indicate that there is a statistically significant difference for newspaper and other paper recycling rates in Miami-Dade and Broward Counties before and after they switched to SSR. This might be because of the high potential for recycling in these counties in light of the higher population and higher number of visitors. The outbound contamination analysis of 35 samples from the OCC and 266 samples from the ONP stream showed that only 31.4% of the OCC samples exhibit lower contamination rates than allowable limits for both outthrows and prohibitive materials. All samples in the ONP stream have higher contamination rates than the paper mills allow for at least one of the contamination types (brown paper, outthrows, or prohibitive materials). The most common prohibitive materials for both the OCC and ONP streams are residue and MRF plastic film. This study provides a comprehensive quantitative analysis on the impact of SSR on contamination rates in inbound and outbound material streams, and in different waste generator sectors for two counties in Florida.

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8 APPENDICES

APPENDIX A: MATERIAL DEFINITIONS

In this report, we used same material definitions used in waste composition studies provided by Kessler Consulting Inc.

TABLE 12. Material definitions in waste composition studies.

Category	Sub-Category	Description/Examples
PAPER	Newspaper	Newspaper (loose or tied) including other paper normally distributed inside newspaper such as ads, flyers, etc. Newspaper found inside plastic sleeve will be removed from plastic and sorted accordingly.
	Corrugated Cardboard (OCC)	Brown "cardboard" boxes with a wavy core (no plastic liners or packaging Styrofoam®). Does not include small pieces of OCC within shrink wrap plastic such as that from a case of bottled water.
	Waxy Cardboard	All wax coated OCC will be sorted and weighed separately from non-wax OCC.
	Mixed Paper	Printed or unprinted paper including white, colored, coated and uncoated papers, manila and pastel colored file folders magazines, telephone books, catalogs, paperboard, chipboard, brown paper bags, mail, bagged shredded paper and other printed material on glossy and non-glossy paper.
	Loose Shredded Paper	Loose shredded residential mixed paper or newspaper.
	Aseptic Containers	Gable top milk cartons, juice boxes, and other similar containers.
PLASTIC	PET Bottles (SPI #1) Polyethylene terephthalate	Clear and colored plastic bottles coded PET #1 such as soda bottles, water bottles label with SPI #1. *Does not include loose caps.*
	NATURAL HDPE Bottles (SPI #2) High-density polyethylene	Clear/natural plastic bottles coded HDPE #2 such as milk jugs, vinegar bottles and gallon water bottles. *Does not include loose caps and lids.*

	COLORED HDPE Bottles (SPI #2) High-density polyethylene	Pigmented plastic bottles coded HDPE #2 such as detergent, shampoo, and orange juice bottles. *Does not include loose caps and lids.*
	Non Bottle PET	Clear and colored plastic items labeled PET #1 such as clamshell containers, frozen food trays, disposable cups and other items labeled PET #1.
	Non Bottle HDPE	Wide-mouthed tubs and containers labeled HDPE #2 including lids. Examples include yogurt cups, margarine tubs, Cool Whip® tubs and other non-bottle HDPE items.
	Expanded Polystyrene (Styrofoam)	Styrofoam® containers such as egg cartons and clamshell food containers.
	Mixed Plastic Containers	All plastic containers coded #3-#7, such as containers, pill bottles, Arizona Iced Tea™ gallon jugs, etc.
	Bulky Rigid Plastics	Consists of non-container rigid plastic items such as plastic drums, crates, buckets, baskets, toys, refuse totes, and lawn furniture, flower pots, laundry baskets, and other large plastic items. *Does not include electronic toys.*
	Plastic Film (Residue)	Loose and bagged plastic bags, garbage bags, shrink wrap, re-sealable bags, etc.
	Non Container Expanded Polystyrene (Styrofoam) (Residue)	Non-container Styrofoam® such as packaging peanuts and other packaging.
GLASS	Mixed Glass Containers and Jars (Glass Containers)	Clear, Green, and Amber glass bottles and jars as well as broken glass pieces larger than ½ square inch.
METALS	Aluminum Cans	Aluminum soft drink, beer, and some food cans.
	Aluminum Foil and Pie Plates	Aluminum foil, pie plates, and clean catering trays.
	Tin/Steel Cans	Tin-plated steel cans, usually food containers, and aerosol cans, including labels. Also includes steel caps.
	Scrap Metals Rejects	Non-container ferrous scrap metals such as pipes, coat hangers, and miscellaneous scrap metal.
RESIDUE	Rejects	Materials not included in the other categories, such as bagged garbage, fast food lids and straws, CDs and VHS tapes, composite materials, Christmas lights, hoses, electronics, recyclable items full of food (non-liquid), loose plastic caps and lids, or plastic cutlery and plates.

	Grit	All items that fall through a half inch mesh.
	Liquids	All liquids found within recyclable containers.

APPENDIX B: ANALYSIS OF VARIANCE

ANOVA (analysis of variance) is commonly used to compare differences of means between more than two groups in the literature. It can be used in both experimental and observational data. ANOVA analyzes this by looking at variation in the data. ANOVA considers both the amount of variation between groups and within groups.

In the studies, when taking a sample rather than measuring the whole population, sampling error needs to be considered in comparing differences in means among different groups. ANOVA basically answers this question. Is the difference between groups greater than sampling error? In other words, is there a real difference in the population means in different groups?

ANOVA can be represented mathematically as:

$$x_{ij} = \mu_i + \epsilon_{ij} \tag{1}$$

In the equation (1), x_{ij} denotes the individual data point for group i and observation j, ϵ shows the unexplained variation and μ_i shows the population mean of group i. Based on Equation (1), each individual data point can be represented as its group mean and error term.

Hypothesis testing

Similar to other statistical tests, ANOVA calculates a test statistic, the F-ratio. Using the F-ratio, one can obtain the probability, called the p-value, of obtaining the data assuming the null hypothesis. Based on the p-value, it is determined if at least one group's mean is statistically different from the others. Usually if the p-value is smaller than 0.05, it is concluded that there is statistical evidence for the alternative hypothesis.

H_0: $\mu_1 = \mu_2 = \cdots = \mu_k$
H_1: Means are not all equal

Here H_0 is the null hypothesis, which means all population means are equal, and H_1 is the alternative hypothesis.

F-ratio calculation

As discussed above, ANOVA separates the variation in the data into two parts: between-group and within-group. As shown in Table 7 in the report, these variations are called the sum of squares. Particularly, SS_B shows the between-group variation and SS_W shows the within-group variation. The calculations of SS_B and SS_W in the case of K groups with total N observations are given in the following equations.

$$SS_B = \sum_{i=1}^{K} n_i(\bar{X_\iota} - \bar{X})^2 \tag{2}$$

$$SS_W = \sum_{i=1}^{K} \sigma_i(n_i - 1) \tag{3}$$

In Equations (2) and (3), n_i is the number of observations in group i, $\overline{X_i}$ is the mean of group i, σ_i is the variance of the group i and $\bar{X}$ is the population mean. In the calculation of F-ratio, the mean squares are used. It is computed by dividing sums of squares by degrees of freedom. Degrees of freedom is $K-1$ for SS_B and $N-K$ for SS_W. The calculation of mean squares is given in the following.

$$MS_B = \frac{SS_B}{K-1} \quad (4)$$

$$MS_W = \frac{SS_W}{N-K} \quad (5)$$

After the calculation of mean squares, the F-ratio is computed as:

$$F - ratio = \frac{MS_B}{MS_W} \quad (6)$$

Then, to obtain the p-value, F-ratio is tested against the F-distribution of a random variable with degrees of freedom associated with MS_B and MS_W. The summary of ANOVA is shown in Table 13.

TABLE 13. Summary of ANOVA formulas.

Source of variation	**Sum of squares**	**Degrees of freedom**	**Mean square**	**F ratio (test statistic)**
Between	$SS_B = \sum_{i=1}^{K} n_i(\overline{X_i} - \bar{X})^2$	*K-1*	$MS_B = SS_B$ / (*K-1*)	MS_B / MS_W
Within	$SS_W = \sum_{i=1}^{K} \sigma_i(n_i - 1)$	*N-K*	$MS_W = SS_W$ / (*N-K*)	
Total	$SS_T = SS_B + SS_W$	*N-1*		

APPENDIX C: MANOVA RESULTS

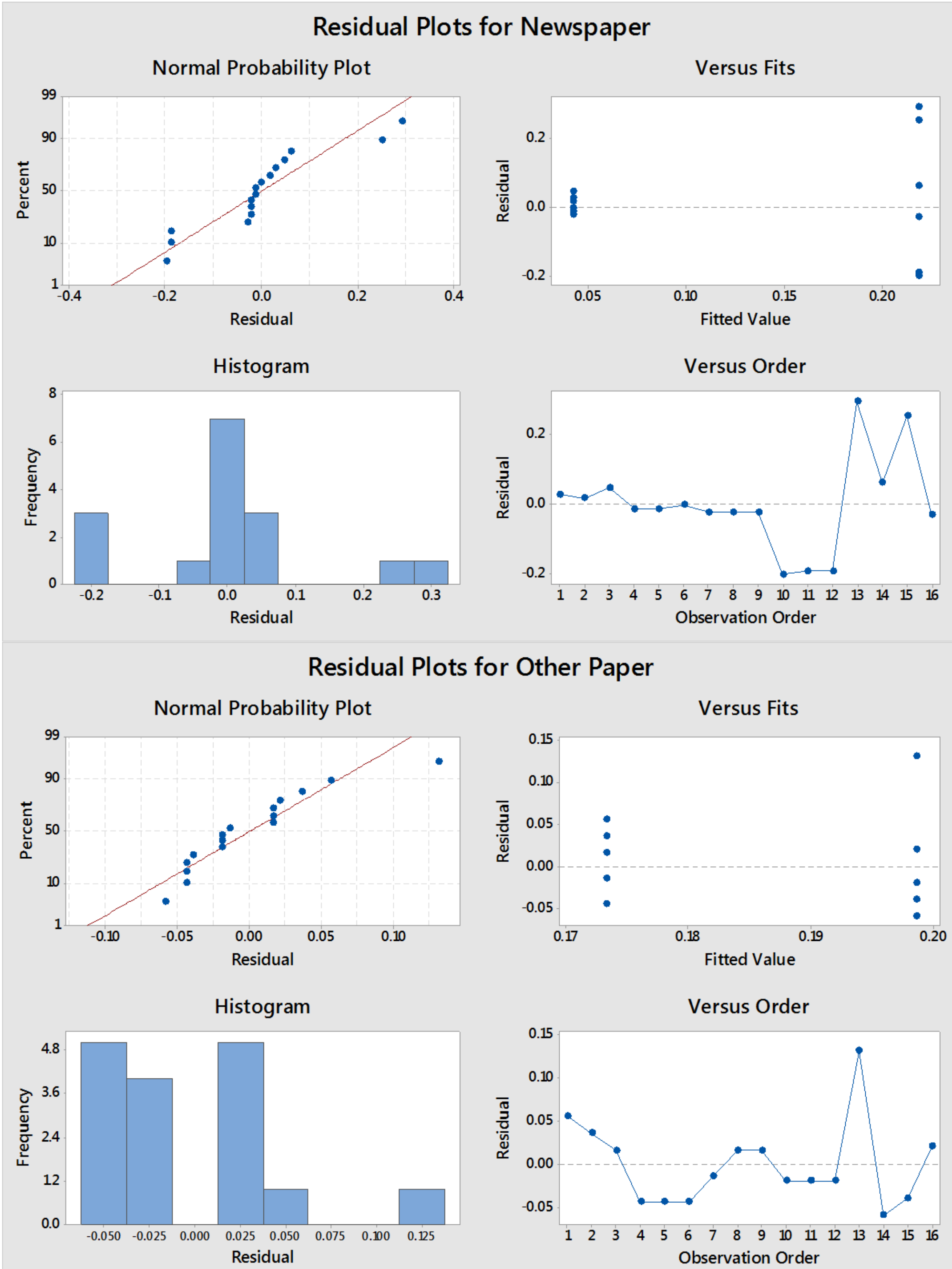

FIGURE 27. Brevard County MANOVA results for comparing newspaper and other paper recycling rates before and after switching to SSR.

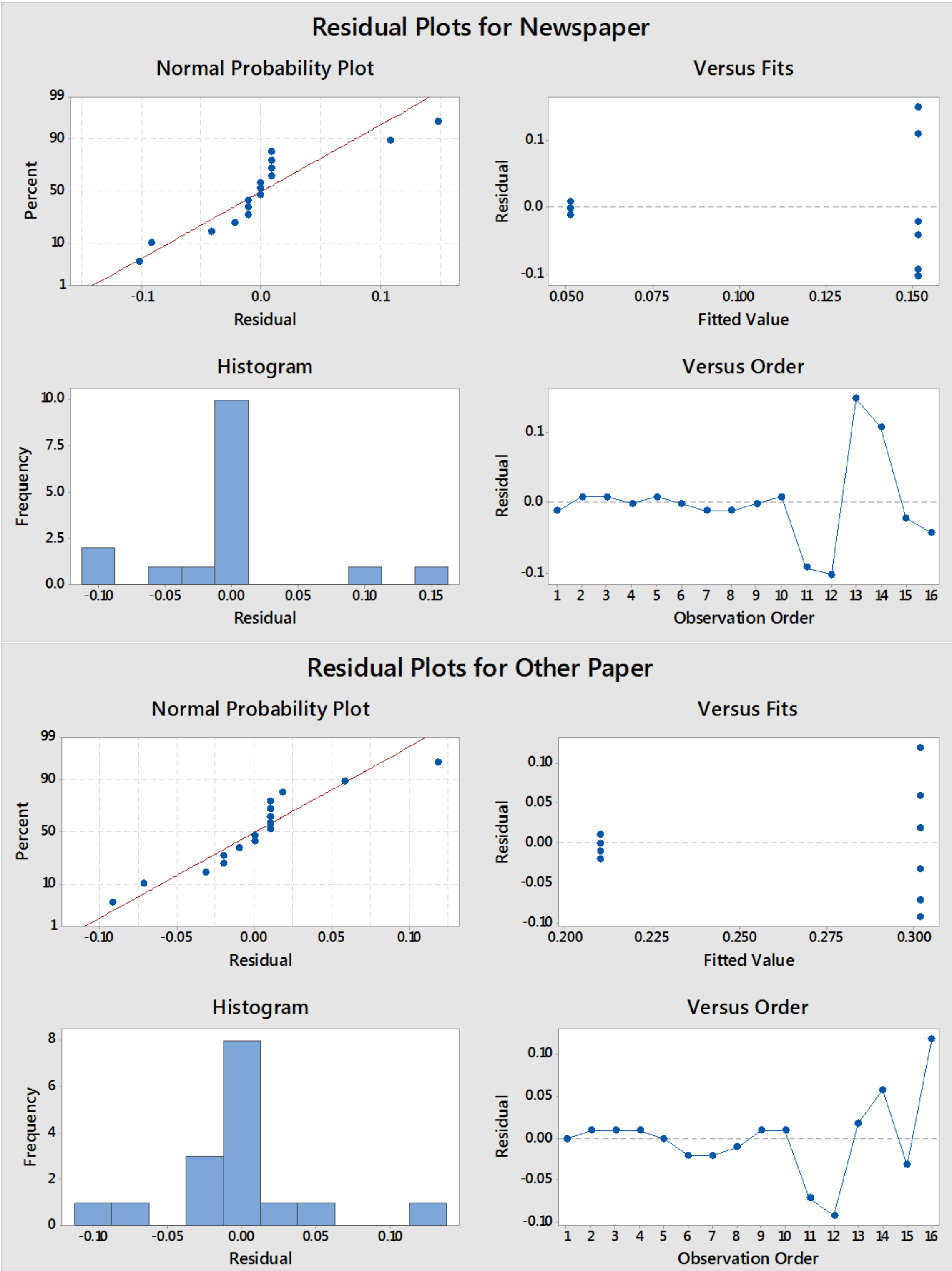

FIGURE 28. Broward County MANOVA results for comparing newspaper and other paper recycling rates before and after switching to SSR.

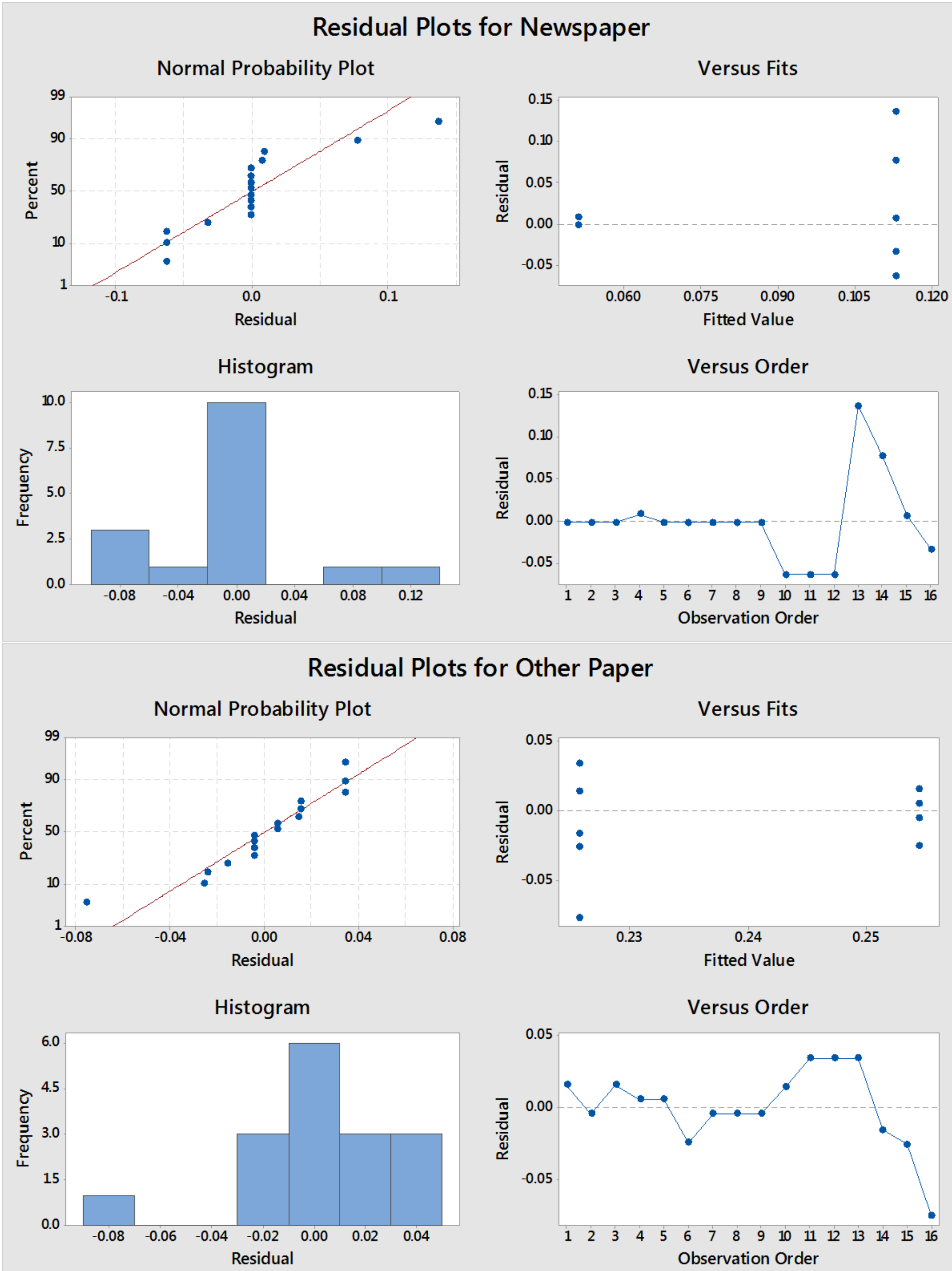

FIGURE 29. Miami-Dade County MANOVA results for comparing newspaper and other paper recycling rates before and after switching to SSR.