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WASTE COMPOSITION ANALYSIS AS A SUPPORT MECHANISM FOR CIRCULAR ECONOMICS

ANALÝZA SLOŽENÍ ODPADŮ JAKO PODPŮRNÝ NÁSTROJ PRO CIRKULÁRNÍ EKONOMIKU

MASTER'S THESIS

DIPLOMOVÁ PRÁCE

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Assignment Master's Thesis

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As provided for by the Act No. 111/98 Coll. on higher education institutions and the BUT Study and Examination Regulations, the director of the Institute hereby assigns the following topic of Master's Thesis:

Waste composition analysis as a support mechanism for circular economics

Brief Description:

Municipal waste management represents the key to closing the loop at the downstream process for a circular economy. Handling municipal waste is one of the most challenging due to its composition and dynamic characteristic, where the distribution and amount are linked to consumption patterns. It is an important material stream with considerably high material but also energy potential. Material re–usage of municipal waste is crucial for the waste treatment hierarchy. Within circular economics, the pushed idea is to use materials suitable for recycling, especially for meeting the set separation goals. In the case of energy potential, this is direct energy use and production of alternative fuels or biogases.
The task will take care of a detailed analysis of the waste composition, especially the evaluation of the results and will recommend suitable procedures for selected streams with a focus on the material and energy use of municipal waste in typical technologies. Part of the analysis will be a description of the requirements for the considered methods of waste utilization. The connection with the preferred material use of municipal waste will also be described, specifically with the requirements connected to the Waste Management Law (541/2020 Coll.) and the technical and economic possibilities of processing waste into secondary raw materials.

Master's Thesis goals:

Certified methodology for the waste composition determination – TIRSMZP719
Procedures and methodologies for determining the composition of waste on a global scale
Analysis of data sets to determine the waste composition
Identification of material flows for creating scenarios
Analysis and technical–economic evaluation of selected municipal waste streams

Recommended bibliography:

Kropáč, J.; Gregor, J.; Pavlas, M. Municipal Waste Composition Analysis – Approaches to and Solutions for Czech Waste Management. In 2nd International Conference on Technologies & Business Models for Circular Economy: Conference Proceedings. Portorož, Slovinsko: University of Maribor Press, 2020. s. 1-10. ISBN: 978-961-286-353-1.

Mavridis, S., Voudrias, E. A. (2021). Using biogas from municipal solid waste for energy production: Comparison between anaerobic digestion and sanitary landfilling. Energy Conversion and Management, 247, 114613.

Deadline for submission Master's Thesis is given by the Schedule of the Academic year 2022/23

In Brno,

L. S.

prof. Ing. Petr Stehlík, CSc., dr. h. c. Director of the Institute	doc. Ing. Jiří Hlinka, Ph.D. FME dean

ABSTRACT

The diploma thesis focuses on the application of waste composition analysis to facilitate the transition of waste management towards a circular economy, thereby promoting sustainable development. The first part of the thesis covers the introduction to the topic of waste management and the circular economy, followed by an exploration of the techniques and tools for performing waste composition analysis. The second part presents a detailed analysis to identify the waste composition at the first and third levels with a focus on municipal waste. The waste composition analysis is based on a certified methodology that was created as part of the TIRSMZP719 project. The data management was conducted primarily by Visual Basic for Application (VBA) programming. The results of the waste composition analysis are illustrated through diagrams, allowing for the identification of possible trends and waste stream variation across the studied time of municipal solid waste. The applicability of the tool in suggesting suitable waste treatment and recovery implementations based on the identified waste composition is demonstrated through a case study of Brno municipality. The analysis reveals that biowaste comprises the highest proportion (23.17%) of municipal solid waste, with food waste identified as the main waste composition at the third level assessment. This finding proposes high feasibility and potential for biogas production. The waste treatment solution for the other waste composition is also suggested in this thesis. Such assessment is important and could lead to the potential reduction of municipal solid waste by approximately 40% through the enabling of targeted strategies for resource recovery. This finding is very important, because the overall designed conception can respond to this separation potential, which is linked to stated goals or other obligations related to the goals of the Waste Management Plan of the Czech Republic. The proposed assessment emphasizes the proposed goals and shows the potential for their fulfilment.

KEY WORDS

Municipal solid waste, waste composition analysis, circular economy, biodegradable waste, TIRSMZP719, recycling

ABSTRAKT

Předkládaná diplomová práce se zaměřuje na využití analýzy složení odpadu k usnadnění přechodu lineárního odpadového hospodářství na oběhové hospodářství. První část práce se zabývá úvodem do tématu odpadového a oběhového hospodářství, po kterém následuje seznámení s technikami a nástroji pro provádění analýzy složení odpadu. Druhá část práce představuje detailní analýzu, která identifikuje složení odpadu na první a třetí úrovni se zaměřením na komunální odpad. Složení odpadu vychází z certifikované metodiky, která vznikla v rámci projektu TIRSMZP719. Správa a analýza dat byla prováděna především za pomocí programovacího jazyka Visual Basic for Application (VBA). Výsledky analýzy složení odpadů jsou znázorněny pomocí grafů, které umožňují identifikovat možné trendy a rozdíly v toku odpadů v rámci zkoumaného období, území či jiného parametru. Použitelnost nástroje při navrhování vhodných způsobů úpravy a využití odpadů na základě zjištěného složení je prezentováno na případové studii města Brna. Z analýzy vyplývá, že největší podíl (23,17 %) směsného komunálního odpadu tvoří bioodpad, přičemž jako hlavní složka bioodpadu byla identifikována složka potravinových odpadů. Toto zjištění navrhuje vysokou proveditelnost a potenciál pro výrobu bioplynu. V této práci je rovněž navrženo řešení zpracování odpadu i pro ostatní složky směsného komunálního odpadu. Takové zhodnocení je klíčové a mohlo by vést k potenciálnímu snížení množství směsného komunálního odpadu až o 40 %. Toto zjištění je velmi důležité, protože celková navržená koncepce dokáže odpovědět právě na separační potenciál, který je navázán na stanovené cíle či jiné závazky související s cíli Plánu odpadového hospodářství ČR. Navržené posouzení akcentuje navržené cíle a ukazuje potenciál pro jejich splnění.

KLÍČOVÁ SLOVA

Směsný komunální odpad, analýza složení odpadu, cirkulární ekonomika, biologicky rozložitelný odpad, TIRSMZP719, třídění

ROZŠÍŘENÝ ABSTRAKT

Zrychlený životní styl a neustálý růst počtu obyvatel a průmyslové činnosti po celém světě vede k výraznému nárůstu produkce odpadů. Nakládání s odpady, jejich zpracování a likvidace patří mezi zásadní problémy současnosti. Tyto problémy jsou vztaženy zejména na nesprávnou likvidaci (skládkování) odpadů což má dopady na životní prostředí a lidské zdraví. Nesprávný přístup k nakládání s odpady přináší vážné následky, které mohou ohrožovat existenci člověka a mají nevratný dopad na celou planetu. Důsledky nevhodného nakládání s odpady můžeme pozorovat v každém koutě světa. Jako konkrétní příklad lze uvést situaci v Bosně a Hercegovině, kde byl odpad „ukládán“ do řeky Drina, která se následně proměnila v tekoucí skládku. Jako další příklad lze uvést sesuv přeplněné skládky v Etiopii, který způsobil ztráty na lidských životech a značné škody na životním prostředí. Právě tyto události zdůrazňují potřebu řádného monitorování a zpracování odpadů.

Aby nedocházelo k nesprávnému nakládání s odpady vydává Evropská unie celou řadu rozhodnutí, zabývajících právě touto problematikou např. Waste Framework Directive, A new Circular Economy Action Plan. Jedním z klíčových přístupů využívaných při řešení otázek nakládání s odpady, je tzv. oběhové hospodářství. Cílem oběhového hospodářství je podpora minimalizace tvorby odpadů a následně přeměna již vzniklého odpadu na zdroje, které mohou být znovu využity ve výrobním procesu jako druhotná surovina. Jedná se tedy o uzavřený koloběh, kde v ideálním případě, bude vznikat jen minimum odpadů, které nebude možné dále efektivně využívat. Je snaha, aby právě oběhové hospodářství nahrazovala tzv. lineární hospodářství. Kromě těchto koncepčních přístupů je nutné dokázat analyzovat jednotlivé toky odpadů či se zabývat jejím složením. Tento krok je klíčový, aby bylo možné identifikovat, které materiály jsou ještě materiálově využitelné, resp. materiály budou využity už jenom jako palivo. V tomto ohledu je důležité se zabývat právě analýzou složení odpadů, která je hlavním předmětem předkládané diplomové práce. Analýza složení odpadu je užitečným a do budoucna bude chtěným nástrojem. Cílem analýz je zvolit takové metodiky, které budou využitelné pro širší spektrum odpadů. Využitím analýzy složení odpadu je možno navrhnout doporučení, která mohou efektivně podpořit např. systém sběru odpadu, frekvenci či optimalizaci odpadového hospodářství na posuzovaném území. Výsledky analýzy lze rovněž využít v rozhodovacích procesech spojených související s výstavbou nových zpracovatelských zařízení. Příslušné instituce, které jsou odpovědné za nakládání s odpady, mohou na základě analýzy složení odpadu určit nejefektivnější a nejúčinnější metody, jak s odpadem nakládat. Detailní znalost složení odpadu rovněž pomáhá při posuzování potenciálních rizik spojených s nakládáním s odpady a při určování vhodných metod jeho zpracování s ohledem na minimální dopad na životní prostředí. Znalost složení vstupních surovin například umožňuje provozovatelům bioplynových stanic upravit parametry zpracování a zajistit optimální produkci bioplynu, což zvyšuje výrobu energie a využití zdrojů. To samé platí např. u plastů, papíru, skla, kovů a další. Kromě samotného složení odpadu je nutné se zabývat i zpracováním dat a vyhodnocování vhodných závěrů.

Diplomová práce má jeden z vytyčených cílů vytvořit nástroj, který dokáže pracovat s rozšířenými datovými sadami z rozborů a vyhodnocovat patřičné závěry dle uživatelem zvolených požadavků na výstupy.

Odpadové hospodářství v jednotlivých členských státech Evropské unie se řídí hierarchií nakládání s odpady, jak byla definována Evropskou komisí. Hierarchie řadí možnosti nakládání s odpady tak, aby bylo co nejméně škodlivé pro životní prostředí a lidské zdraví. Hierarchie

dává největší důraz na předcházení vzniku odpadů, posléze se přiklání k přípravě k opětovnému použití, následně k recyklaci odpadů a poté k energetické využití odpadů. Nejméně vhodným zpracováním odpadů je dle hierarchie skládkování odpadů.

Tématem diplomové práce je analýza složení odpadu jako podpůrný nástroj pro cirkulární odpadu. Cílem teoretické části je úvod do problematiky odpadů a pochopení principů analýzy složení odpadů. Hlavním cílem praktické části je využití získaných datových sad z analýzy směsného komunálního odpadu a jejich zpracování do vhodné podoby pro potřeby různých územních celků. Složení odpadu vychází z certifikované metodiky, která vznikla v rámci projektu TIRSMZP719. Správa a analýza dat byla prováděna především za pomocí programovacího jazyka Visual Basic for Application (VBA). Výsledky analýzy složení odpadů jsou znázorněny pomocí grafů, které umožňují identifikovat možné trendy a rozdíly v toku odpadů v rámci zkoumaného období, území či jiného uživatelem zvoleného parametru. Nedílnou součástí práce je případová studie, která využívá nástroj analýzy složení odpadů s vazbou na doporučení pro nakládání s odpady zejména se zaměřením na biologicky rozložitelný odpad.

V teoretické části jsou dále představeny metody nakládání s odpady. Teoretickou část práce uzavírá představení dvou metodik analýzy složení odpadu. Konkrétně se jedná o metodiku SWA Tools, která byla zavedena Evropskou komisí a o českou certifikovanou metodiku, která byla vytvořena Ústavem procesního inženýrství z Vysokého učení technického v Brně v rámci projektu TIRSMZP719.

Praktická část diplomové práce se zabývá popisem procesu získávání prvotních dat analýzy složení odpadů na základě certifikované metodiky TIRSMZP719. Prvním krokem analýzy složení odpadu je odběr nádob a tvorba reprezentativního vzorku. Následuje roztřídění dílčího nebo reprezentativního vzorku na stanovené odpadové složky až na 45 frakcí (záleží na zvoleném třídicím modulu). Oba procesy jsou detailně popsány v certifikované metodice. Údaje o vytříděném vzorku se zapisují do rozhraní programu Excel. Aby bylo možno sledovat změny daných odpadních toků v směsném komunálním odpadu a zjistit jejich průměrnou hodnotu ve sledovaném časovém horizontu, byl naprogramován skript prostřednictvím VBA. Skript umožňuje filtraci a přepočet hodnot z databáze rozborů (cca 650 dílčích vzorků) a jeho výsledky ukazují vážené aritmetické hodnoty daných toků odpadů a frakcí v první a třetí úrovni. Vytvořený skript také umožňuje uživateli filtrovat data v závislosti na zvolené obci, kde analýza složení odpadu proběhla, časové hledisko či další parametry, které jsou relevantní pro hodnocení. Pro každý výsledek bylo vytvořeno několik grafů a jsou zohledněny trendy, kterou jsou komentovány. Výsledky ukazují vysokou koncentraci proudu biologicky rozložitelného odpadu v směsném komunálním odpadu. V průměru se tato hodnota pohybuje cca kolem 30 %. Takové množství má vysoký potenciál pro procesy materiálového využití, kde se mezi nejvhodnější procesy pro biologicky rozložitelný odpad řadí aerobní a anaerobní fermentace.

Navržená případová studie obce seznamuje s výsledky analýzy složení odpadů na první úrovni (rozdělení dle jednotlivých komodit). Případová studie následně propojuje poznatky získané z praktické části o třetí úrovni studovaných odpadních toků s prezentovanými výsledky. Toto spojení umožňuje doporučit technologie pro potenciální nakládání s odpady. Práce uvádí dvě možná řešení bioplynové stanice, která by využívala biologicky rozložitelný odpad. Takové řešení by vedlo ke snížení produkce směsného komunálního odpadu a odpadu uloženého na skládkách, a tím snížila dopad směsného komunálního odpadu na životní prostředí. Snížení plastové a papírové složky v směsného komunálního odpadu bude dosaženo za pomocí využití sítě dotřiďovacích linek a zvýšení povědomí a motivace veřejnosti k třídění a následné recyklaci daných složek. Realizace prezentovaných řešení případové studie pro toky biologicky rozložitelných, plastových a papírových složek odpadů povede k potenciálnímu snížení produkce směsného komunálního odpadu na téměř polovinu jeho původní hodnoty. Za předpokladu, že veškerý využitelný potenciál bude využit v dotčených složkách. V kontextu cílů Plánu odpadového hospodářství České republiky by směsný komunální odpad představoval pouze 28 % z celkového komunálního odpadu vyprodukovaného na území České republiky. Důsledkem snížení množství vyprodukovaného směsného komunálního odpadu bude požadavek na zvýšení objemu materiálového využití, tj. recyklace. Tento krok směřuje k principu oběhového hospodářství.

Navrhovaný koncept řešení by umožnil zvýšit objem recyklace a znovuvyužití odpadu až na cca 70 % z celkového množství vyprodukovaného komunálního odpadu , který vychází z třídícího modulu TIRMSZP09. Cíle, které jsou stanoveny dle Zákona č. 541/2020 Sb. - Zákon o odpadech, odpadového hospodářství České republiky vyžadují v časovém horizontu do roku 2035 navýšit objem recyklace a znovuvyužití na 65 % vyprodukovaného komunálního odpadu, který vychází z třídícího modulu TIRMSZP09. Tohoto cíle lze s dostatečným úsilím dosáhnout za předpokladu stoprocentního přesměrování. Hodnoty cca 70 % možného využití odpadů lze dosáhnout při teoretické realizaci uvedené v případové studii pro toky papíru, plastů a biologicky rozložitelných odpadů, které by teoreticky měly být plně využity ze směsného komunálního odpadu.

Stanovené cíle diplomové práce byly splněny a práce představuje užitečný nástroj pro zpracování dat z rozborů pro odpadové hospodářství. Diplomová práce představuje možné aplikace nástroje a také automatizuje a optimalizuje proces získávání výsledků.

BIBLIOGRAPHY

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DECLARATION OF AUTHENTICITY

I declare that the thesis entitled, “Waste composition analysis as a support mechanism for circular economics” is my own work and that all the sources that I have used or quoted have been listed and acknowledged at the end of the thesis.

In Brno on 26.05.2023 ……..……..……………………………………………..

Bc, Samuel Halamíček

ACKNOWLEDGEMENT

On this place, I would like to thank my master thesis supervisor, M.Phil. Yee Van Fan, Ph.D., for her professional guidance and support.

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1 INTRODUCTION

The continuous growth of the population and industry activity worldwide has led to a significant increase in waste production. Waste management, treatment, and disposal become one of the most important topics due to the potential harmful effects on the environment and human health. Improper waste management decisions can cause severe consequences that harm humanity and will have an irreversible impact on the planet. An example of inadequate waste management can be mentioned the situation in Bosnia and Herzegovina, where the waste has been disposed of in the local rivers, with the Drina River getting clocked by the amount of disposed waste in January 2023. Another case of deterrence can be mentioned landslide of an overfilled landfill in Ethiopia, which caused the loss of human lives and significant environmental damage. These incidents underscore the urgent need for proper monitoring and waste treatment to prevent the recurrence of such issues.

To prevent such accidents and mitigate the impact of waste on the environment, the European Union has been publishing documents concerning waste management, hierarchy and recommendations connected to these topics. One key concept that emerges to address these issues is a circular economy. The circular economy approach aims to promote waste minimization as well as the transformation of generated waste into valuable resources, which can be reintroduced into the manufacturing process as secondary raw material. To decide on the specific types of waste treatment and logistics in waste management, waste composition analysis comes onto the scene. Waste composition analysis is a useful tool not limited to municipal waste but applicable across different waste categories for decisions connected with the collection process and possible investments into new technologies. Authorities can determine the most efficient and effective method for the collection process based on waste characteristics. The composition of these wastes significantly influences the level of payment required for their treatment. Accurate knowledge of the composition aids in assessing the potential risks, determining appropriate treatment techniques and optimizing the production process with minimal environmental harm. For example, understanding the feedstock composition enables biogas plant operators to adjust processing parameters and ensure optimal biogas production, enhancing energy generation and resource recovery. The right usage of waste composition analysis for municipal solid waste with all connected data management processes is aimed to be accomplished across the master thesis.

2 MOTIVATION, GOAL, SCOPE OF STUDY

Waste management is the key to closing the loop at the downstream process for a circular economy and is among the most important topics in today's society. The aim of the thesis is to assess and develop a tool based on existing procedures for solid waste analysis, which could mitigate the challenges of waste management and facilitate the transition towards a circular economy. An in-depth understanding of solid waste composition and characteristics will significantly enhance decision-making and enable investment in advanced waste treatment technologies.

The master thesis presents theoretical information connected with waste management, waste policy connected, and details about solid waste analysis. In the practical part, the thesis will present results connected with the use of solid waste analysis. Presented results can be used for decisions in the waste treatment area. Results from the solid waste analysis can identify potential valuable resources and fractions to which should be paid attention to. As a part of the thesis, the results will be used for a practical treatment recommendation of potentially useful waste streams.

The waste management and waste policy should follow the waste hierarchy defined by the EU Waste Framework. The hierarchy ranks the options of waste management in a way to be the least harmful to the environment and human health. The waste hierarchy is established as and shown in Figure 2-1 [1], [2]:

- Prevention of generation of waste (most preferable option)
- Re-use of the waste
- Recycling
- Recovery
- Disposal on landfills (least preferable option)

Figure 2-1 Waste hierarchy in a look at the EU and Czech Republic [1], [2]

3 WASTE MANAGEMENT

Waste can be defined as a piece of material or a product which is no longer useable, does not hold any marginal value to the owner and where the owner decided to discard the item. The item becomes waste in its afterlife cycle. The start of the afterlife cycle is dependent on different factors. In waste management problematics, waste is divided into two main categories – Municipal and Industrial waste [3], [4].

Municipal waste is created by human activity. The diversity of products, industries, and activities enables the creation of many different types of waste. To understand the differences between certain types of waste, it is necessary to use separation into categories. The legislation provides a uniform separation process. Waste composition analysis creates an opportunity for a logical and organized approach to municipal waste problematics. Municipal waste can also be referred to as municipal garbage or municipal refuse [3], [4].

Industrial waste is generated by for example the factories for chemical, biological, mechanical engineering businesses, and other industrial enterprises. Compared to municipal waste, the composition of the industrial waste is more homogenous. The company is responsible for the generated waste and the waste management plan should be part of the company's business strategy [3]–[5].

The expansion of industries, population and global wealth and urbanization comes in hand with the rise of total municipal waste produced. Waste handling, storing, and disposing can pose risks to the environment and the human body. Municipal waste management creates challenges throughout social, economic, and environmental areas. Effective waste management is essential to ensuring a clean, healthy, and sustainable environment for current and future generations Indicated problems and challenges of municipal waste management are described in more detail through the theoretical part of the thesis [3], [6].

Municipal waste management involves a wide range of activities which aim for the prevention of waste generation, waste stream management, waste treatment, and control of waste permanent disposition. For responsible and safe waste management the actions taken should comply with the legal requirements given by the legislative. Waste management should be established as a part of the country's legislative. Waste management of countries situated in the European Union is following the strategy and hierarchy given by Waste Framework Directive. The right strategy in Waste management enables lower the harmful impact of the generated waste on public health and pushes society towards a more sustainable environment [3], [6].

3.1 DEFINITION OF MUNICIPAL SOLID WASTE (MSW)

Municipal solid waste (MSW) is referred to as non-hazardous waste in a solid or semi-solid state. MSW is produced by households, streets, commercial sectors, and other institutions connected to the urban area. The waste generated in the industrial sectors can be considered due to the possibility of mixing and ending in the MSW stream [4], [6].

MSW is the most general category within the waste composition problematics. It is important to distinguish the terms 'municipal waste' and 'municipal solid waste' (MSW). Municipal waste encompasses a wide range of waste streams, where the MSW is one of the mentioned waste streams. MSW is a subsystem of municipal waste. MSW typically contains organic waste, such as food and its leftovers, waste created through gardening activities, and inorganic waste such as paper, plastic, glass, metals, textiles etc. The municipal waste composition is primarily comprised of MSW[3], [4], [6].

Depending on the country and its definitions of the MSW and laws connected to it, in the MSW can be found commercial, non-hazardous industrial, construction and demolition waste and parts of sewage sludge. The amount of MSW and its composition is dependent on the following factors [3], [4], [6]:

- Country and regions
- Time of the year
- Population density
- Economic conditions
- Willingness into investment
- Regulations given by executive commissions

The changes and trends in the composition of municipal solid waste are studied in the practical part of the thesis.

3.2 WASTE LEGISLATION

Waste legislation is a set of regulations and guidelines critical for the set-up of waste management and the waste management plan. Waste legislation has an impact on anyone who participates in the waste management of controlled waste, which includes waste producers, importers, carriers, keepers, and waste treatment facilities. Usually, waste legislation establishes regulations connected to waste collection, transportation, treatment, and disposal. Waste management in the European Union follows strategies, recommendations, and regulations given by the Waste Framework Directive. Czech Republic's waste management is governed by a series of laws and regulations described later in this chapter. Well-established waste legislation ensures the reduction of the environmental impact of waste and leads towards a sustainable environment [1], [2], [7].

3.2.1 WASTE FRAMEWORK DIRECTIVE

Waste Framework Directive is a set of documents published by the European Parliament and the Council. The Directive defines information connected to waste management and problematics. The Directive aims to protect the environment and human health. These aims shall be accomplished through the reduction and prevention of the generation of waste, the right steps in waste management which leads towards a reduction in the overall impact of resource use and improvement in efficiency in waste treatment processes. Waste Framework Directive enables the possibility of transition into a circular economy [1], [3].

The first Waste Framework Directive was adopted in 1975. For the expression of more accurate goals in waste problematics of today's society, the latest addition to the Waste Framework Directive is a Directive (EU) 2018/851 accepted by the European Parliament and the Council amending Directive 2008/98/EC on waste [1], [3], [8].

The Waste Framework Directive implies the framework, obligations, and duties towards the member states. The laws, legal acts and waste management strategies of the member states should be guided by and consistent with the directives. The cooperation between member states is critical for the achievement of the goals set up by the European Union and the preservation of a sustainable environment [1], [3], [8].

In connection with the master thesis, the Waste Framework Directive states the following important terms:

"Waste means any substance or object which the holder discards or intends or is required to discard." [3]

"Municipal waste means:

a) mixed waste and separately collected waste from households, including paper and cardboard, glass, metals, plastics, bio-waste, wood, textiles, packaging, waste electrical and electronic equipment, waste batteries and accumulators, and bulky waste, including mattresses and furniture;
b) mixed waste and separately collected waste from other sources, where such waste is similar in nature and composition to waste from households;"[3]

"Waste management means the collection, transport, recovery (including sorting), and disposal of waste, including the supervision of such operations and the after-care of disposal sites, and including actions taken as a dealer or broker;" [3]

"Treatment means recovery or disposal operations, including preparation prior to recovery or disposal." [3]

"Recovery means any operation the principal result of which is waste serving a useful purpose by replacing other materials which would otherwise have been used to fulfil a particular function, or waste being prepared to fulfil that function, in the plant or in the wider economy." [3]

"Recycling means any recovery operation by which waste materials are reprocessed into products, materials or substances whether for the original or other purposes." [3]

"Disposal means any operation which is not recovery even where the operation has as a secondary consequence the reclamation of substances or energy." [3]

"By-product. A substance or object resulting from a production process the primary aim of which is not the production of that substance or object. The directive sets conditions under which such a substance or object is not to be considered waste." [3]

The Waste Framework Directive establishes the waste hierarchy, which applies the priority order in waste prevention and management legislation. The waste hierarchy was presented in the second chapter "Motivation, Goal and Scope of Study". In addition to the waste framework directive, European Commission has established additional directives which deal with specific parts of waste management. Legislation presented by the EU leads towards sustainable waste management coordinated by the circular economy idea [1], [9].

3.2.2 WASTE MANAGEMENT IN THE CZECH REPUBLIC

The Waste Act no. 541/2020 Coll. represents and sets up the basics of Waste management In the Czech Republic. The Waste Act no. 541/2020 Coll. is effective since 1.1.2021 and has replaced the previous Waste Act no. 185/2001. The Waste Act 541 introduces the following topics and terms [2], [10]:

- Waste management – hierarchy, duties, obligations, aim, plan
- Waste – definition, categories, records, reporting
- Rights and obligations for persons in the waste management
- Fees in the waste problematics
- Authority of state administration

The waste act draws from the relevant regulations and follows directly applicable regulations established by the European Union. The hierarchy of waste management in the Czech Republic was presented in the second chapter (Figure 2.1) and is in accordance with the directives of the European Union [2], [10].

The Waste Act no. 541/2020 Coll. establishes the following terms which are connected to the master thesis in the first part, paragraph 11:

"i) *Waste recovery, an activity, the result of which is that the waste serves a useful purpose by replacing materials used for a specific purpose or that it is prepared for this specific purpose in such a way that it fulfils the conditions set out in § 9 or 10 and ceases to be waste; methods of waste utilization are listed in Annex No. 5 to this Act*," [10]

"j) *Energy utilization of waste is the use of waste in a manner similar to fuel in order to use its energy content or in another way to produce energy*." [10]

"k) *Material utilization of waste means any method of waste utilization including preparation for reuse, recycling and backfilling, with the exception of energy utilization and reprocessing into materials to be used as fuel or other means of energy production."* [10]

"h) *Recycling means the method of waste utilization, by which waste is reprocessed into products, materials or substances, whether for original or other purposes; waste recycling includes the reprocessing of organic materials but does not include energy recovery and reprocessing into materials to be used as fuel or as backfill material."* [10]

Annex No. 1 to Act No. 541/2020 Coll. introduces the general goals of waste management in the Czech Republic based on the principles of the circular economy and the commitment towards the European Green Deal. The Annex states the percentage amount of municipal waste's weight which shall be recovered. The aim is to obtain 65% of the municipal waste's weight for waste recovery in 2035. No more than 10% of total municipal waste's weight can be disposed of by landfilling by 2035. In connection with energy utilization, in 2035 maximum of 25% of total municipal waste's weight can be energetically utilized. Table 3-1 describes the goals of waste management in the Czech Republic [10], [11].

Aim for the municipal waste	
Year	Amount for reuse and recycle
2025	55%
2030	60%
2035	65%

Table 3-1 – Goals for waste recovery in the Czech Republic [10], [11]

Acceptable waste recovery and treatment technologies are described by the table situated in Annex No. 2 to Act No. 541/2020 Coll. Each type is assigned a recognition tag, which describes allowed waste usage [10].

The waste act does not cover the whole waste problematics, as some specific aspects are regulated by individual laws. For example, packaging waste is described in Act no. 477/2001 Coll. Handling of end-of-life products is regulated by Act no. 542/2020 Coll. Mentioned laws complement the Waste Act no. 541/2020 Coll. in the Czech waste legislation [2].

The Czech waste management plan is set up based on the regulations and guidelines given in the waste legislation. The Waste Act includes a chapter covering the duties connected with the creation of the waste management plan. The Waste act defines municipal waste recycling goals which should be achieved as a part of the waste management plan. Waste composition analysis can be used as a tool in the achievement of municipal waste recycling goals[10], [11].

Waste management in the Czech Republic gives high importance to environmental protection[2], [11].

Czech waste legislative allows progress given by the new EU industrial plan and forces a shift towards a sustainable circular economic system[2], [11].

3.3 CIRCULAR ECONOMY

One of the reasons for the renovation of the waste legislation is the global concern about the classic linear economy model and its impact towards the environment. A typical linear economy model is described with a pattern “take-make-use-dispose”. The linear model pattern uses natural resources to create a product. The product typically does not include an “afterlife” plan and is destined for disposal. Circular economy pursues hinted problems of the linear economy. The circular economy is an economic model which aims towards the sustainable development of products with a describable pattern of “make-use-reuse-remake-recycle”. To ensure a common understanding of the objectives and terminology related to the circular economy among the member states, the European Commission approved the adoption of the Circular Economy Action Plan (CEAP) in March 2020. This chapter is going to describe the circular economy mainly from the view of the European Union. Figure 3-1 illustrates the concept of the circular economy from the perspective of the European Union [12]–[14].

Figure 3-1 Concept of Circular Economy [12]

The concept of a closed-loop system is characteristic of the circular economy. Partial return of the product from the after-life cycle into the development process of the product is a key factor of the circular economy. By the logic of circular economy, waste is viewed as a potential source for subsequent utilization, where disposal should be the last option [12]–[14].

The aims of the circular economy are maximization of resource efficiency and minimalization of the production of waste with increased awareness towards the potential of material recovery of the waste. Shift towards a circular economy should bring the following advantages concerning the environmental, social, and economic fields [12]–[14]:

- Healthier planet and reduction of pollution
- Reduction of dependence on natural and non-renewable resources
- High-quality secondary raw materials
- New local quality jobs and business opportunities
- Greenhouse gas emission reduction

Waste management belongs between critical points in the circular economy. Waste management should follow the waste hierarchy (Figure 2-1) established by the Waste Framework Directive. In connection with municipal waste, the action plan points to the need to increase the proportion of recycled waste in the municipal waste and to lower the amount of municipal waste disposed by landfilling. Changes over the years in the municipal waste treatment methods in the Czech Republic can be found in the yearbook of the Ministry of Environment. The influence of the circular economy towards the Czech legislative can be seen with the pressure towards an increase in the reuse and recycling of the municipal waste in the goals set by the Czech Waste Act 541/2020 described in the previous chapter. The right usage of waste treatment technologies across the waste spectrum is one of the bullet points of the Circular Economy Action Plan [11], [13], [14].

Share in % of selected municipal waste treatment methods in the Czech Republic				
Waste treatment	2018 [%]	2019 [%]	2020 [%]	2021 [%]
Energy utilization	11.70	11.70	12.60	12.10
Material utilization	38.60	41.00	38.60	37.50
Landfilling	46.00	45.90	47.80	47.60
Incineration	0.07	0.06	0.08	0.06

Table 3-2 Municipal waste treatment methods in the Czech Republic during selected years [15]

Table 3-2 describes the percentage of methods of municipal waste treatment in the Czech Republic. Almost half of the municipal waste is disposed of by landfilling and about 38% is materially utilized. The circular economy aims to minimize the municipal waste stream heading to the landfills with an increase in the value of municipal waste recovery. These goals of circular economy respect the established waste hierarchy [14], [15].

The waste management policy of European countries should incline towards the circular economy model. Waste composition analysis is a valuable tool for the revision of municipal waste and identification of waste streams, which are crucial pieces of information in achieving the objectives outlined in the Circular Economy Action Plan and the European Green Deal [12]–[14].

3.4 MUNICIPAL WASTE TREATMENT

One of the most important waste management topics is how to treat the generated municipal waste. The circular economy handles this topic by promoting technologies that will reduce the impact of waste on human health and the environment. Waste treatment can be divided into the following categories[4], [10], [12]:

3.4.1 INCINERATION – WASTE TO ENERGY

Waste to energy is a waste treatment technology that works on the principle of incineration to recover the energy content from the waste. The energy can be used for the generation of electricity or used as a heat source. Municipal solid waste is used as fuel for the incineration process. The waste-to-energy technology can be used in connection with reducing the amount of municipal solid waste in landfills. Waste composition analysis allows for establishing the lower heating value of municipal solid waste. Waste composition is an important parameter for the precise design of waste-to-energy plants. The design of waste-to-energy plants differs with the types of used technologies, but the standard process can be described as[4], [16]:

- Combustion of waste → Heat in flue gas
- Transfer of heat from flue gas to process steam
    - Flue gas → cleaning process → stack
- Superheated steam → steam turbine
- Transfer of heat from the expanded steam to the external heating process stream

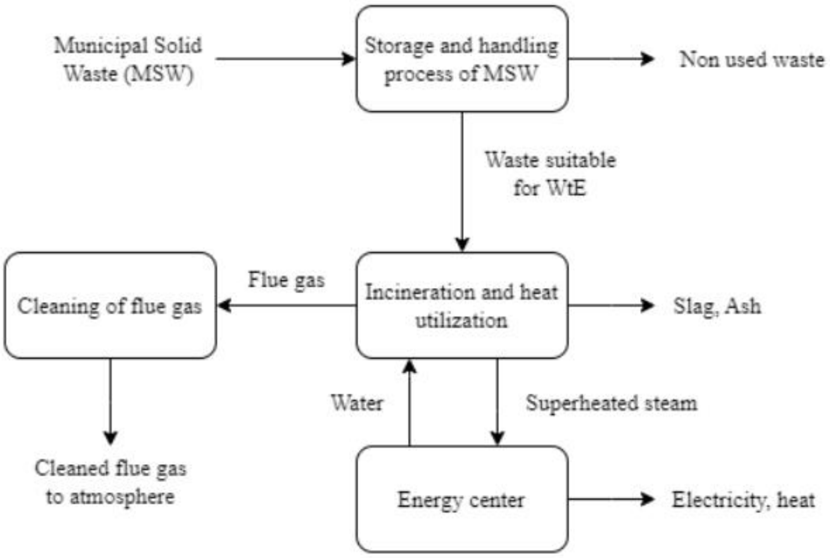

Figure 3-2 Waste-to-energy plant process diagram

Figure 3-2 shows individual processes of possible Waste-to-energy plant. Figure 3-3 shows a possible assessment of individual technologies in an energy-efficient Waste-to-energy plant.

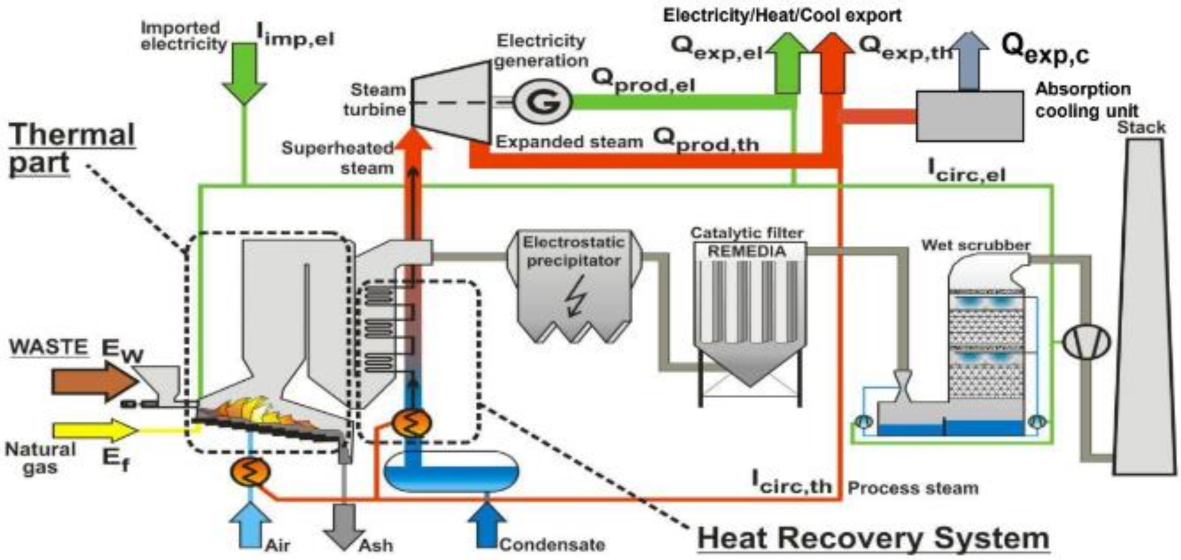

Figure 3-3 Energy efficient assessment of Waste-to-energy plant [17]

3.4.2 LANDFILLING

Landfilling is a waste treatment method where the given solid waste is disposed of in a predestined and managed facility. In connection with the EU's waste hierarchy, landfilling is the least acceptable and the last preferable option for waste treatment. Solid waste disposed in landfill can be potentially dangerous to human life and to the environment due to the possible contamination of ground water and generation of methane during the waste decomposition process. In support of the circular economy, the council of the European Union has established

Council Directive 1999/31/EC on the landfill of waste. The directive recognizes the following types of landfills [3], [18], [19]:

- Landfills for hazardous waste
- Landfills for non-hazardous waste
- Landfills for inert waste.

One of the important goals of the Directive is the reduction of waste disposed of in landfills, with the aim of only 10% of municipal waste being landfilled in 2035. The directive also establishes a restriction for landfilling of waste which is suitable for recycling or other material or energy recovery starting from 2030[19].

3.4.3 RECYCLING – SECONDARY RAW MATERIAL

Recycling is a waste treatment method which aims at the reintroduction of waste into the production process by converting the waste into a secondary raw material. The motivations for recycling are to reduce the impact on the environment and to conserve natural materials during the manufacturing process. Recycling can be divided into [3], [4]:

- Direct – Recovery of waste without necessary treatment (For example use of components from old device)
- Indirect – Recovery of waste by treatment and reprocessing materials from waste

Recycling finds its limitations in the material, technical and economic fields. The economic limits relate to the potential price competitiveness of the produced secondary raw materials compared to the natural raw materials on the open market. The material and technical limits refer to the mass-energy equivalence, where energy losses occur in any kind of technological process of material transformation so that complete recycling of waste materials is not possible. Among the important material limitations of recycling belong the maximum possible number of recycling cycles. As a technological limitation can be mentioned the limited quality of recycling due to the current state of knowledge in this field. Among the most popular recycled waste streams belongs paper, plastic, glass and metal streams. The recycling process can be divided into the following levels [3], [4]:

- Separate waste collection
- Waste sorting
- Waste processing or treatment
- Selling of secondary raw materials

Each level of the recycling process requires equal effort and attention to maximize its effectiveness [4].

3.4.4 BIODEGRADABLE WASTE TREATMENT

Waste treatment methods designed for biodegradable waste are based on the principle of decomposition of the organic parts in the biodegradable waste by microorganisms with the production of solid sludge. Biodegradable waste treatment methods and their technologies can be divided into[4], [20]:

- Recycling into soil
    - Composting

- Energy recovery
  - Anaerobic digestion with the aim of obtaining a biogas
- Industrial recovery
  - Construction and insulation material
  - Celluloses

3.4.4.1 COMPOSTING

Composting, also known as aerobic digestion, belongs between the oldest, simplest, and cheapest solutions for biodegradable waste treatment. Composting is a biotechnological process using the biochemical activity of aerobic microorganisms in the presence of oxygen. The microorganisms break down the organic materials, producing carbon dioxide, water, and heat as by-products. The solid material left after going through the composting process is called compost. Composting can be produced by different methods [4], [20], [21]:

- Composting in the open area
- Intensive composting
- Sack composting
- Vermicomposting

The typical composting process can be described in the following phases [4], [20], [21]:

- Decomposition phase – sanitation (1. – 3. Week)
- Transformation phase (3. – 7. Week)
- Maturation phase (7. – 12. Week)

Aeration is necessary for the right progress in the composting process. Aeration and the associated mixing process increase the rate of compost maturation. Compost can partially replace conventional mineral fertilisers, serving as soil amendments. The replacement will have an impact on minimising the consumption of energy and fossil resources necessary for producing conventional mineral fertilisers [4], [20], [21].

3.4.4.2 ANAEROBIC DIGESTION

Anaerobic digestion is a waste treatment method which uses the organic fraction of municipal solid waste (OFMSW) to generate biogas. Anaerobic digestion is a biotechnological process using the biochemical activity of anaerobic microorganisms without the presence of oxygen. The temperature during the anaerobic digestion ranges from 0°C to 70°C. Apart from mentioned biogas, which is mainly composed of methane and carbon dioxide, anaerobic digestion produces digestate, which in connection with composting is possible to transform into organic fertilizer. The by-products of the process are carbon dioxide and water. Produced biogas can be used for the generation of energy on the cogeneration unit, producing electricity and thermal energy at the same time. Biogas can be also purified into biomethane. Among the most common types of anaerobic digestion belongs[4], [21]–[23]:

- **Dry anaerobic digestion** – Processed biomass contains between 20% to 50% of dry matter
- **Wet anaerobic digestion** – Processed biomass contains less than 14% of dry matter

Typically, a produced biogas contains between 56 to 80% of methane. For the production of the introduced biogas, it is necessary to control the following factors during the process [4], [21]–[23]:

- Temperature – depends on the type of process, ranges between 5°C and 95°C
- Technological factors – mixing of the biomass, retention time
- pH of methanogenic microorganisms – in the reactor should range between 6.5 to 7.5
- Moisture content
- Presence of nutrients
- Presence of toxic and inhibitory substances

A possible solution of anaerobic digestion in a biogas plant is presented in Figures 3-4 and 3-5.

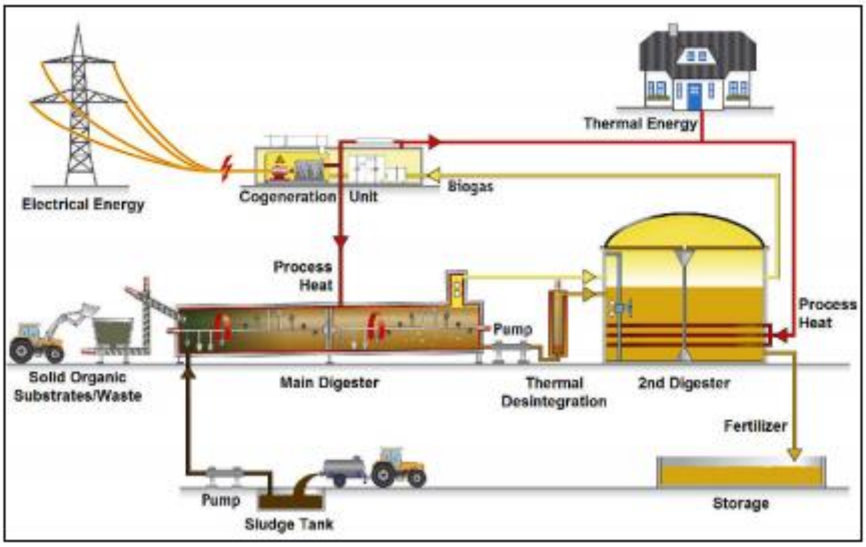

Figure 3-4 Variant of biogas plant [24]

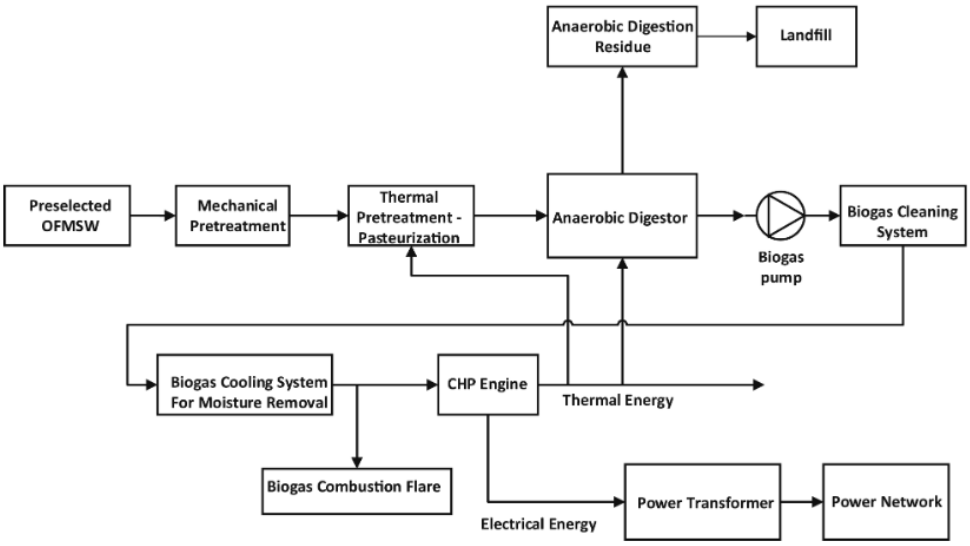

Figure 3-5 Process diagram of possible biogas plant [21]

4 WASTE COMPOSITION ANALYSIS

Waste management has become an important part of modern society. One of the key problems in waste management is the understanding of the composition of the waste. Waste composition analysis is a crucial prerequisite for sustainable development of waste management due to the delivered information about the assessed waste. Waste composition analysis serves as a foundation for developing effective waste management strategies and plans. The waste composition analysis can be used also as valuable information or mechanism for controlling and retrofitting existing strategies. Waste composition analysis plays a vital role in supporting the transition towards a more sustainable, circular economy [25], [26].

The tool and techniques for waste composition analysis are not unified. Local authorities are responsible for waste management and choice of method in their areas. Certain methods can be more suitable for the given type of waste. Different types of waste screening and waste composition analysis are described in the master thesis: "Analysis of municipal solid waste in practice" [26].

Waste composition analysis in this master thesis is conducted based on the approach agreed upon for a national project – "Forecasting waste production and determining the composition of municipal waste" with project number TIRSMZP719. It is based on Solid Waste Analysis Tools (SWA Tools) established by the European Commission in 2004.

4.1.1 METHODOLOGY FOR THE ANALYSIS OF SOLID WASTE (SWA-TOOL) - EU

European Commission established the solid waste analysis tool (SWA Tool) as a part of the fifth Framework Program in 2004 where the official name of the project is "SWA-Tool, Development of methodological Tool to Enhance the Precision & Comparability of Solid Waste Analysis Data. "Aim of the methodology is to give access to the European countries and regions to unify and standardize waste analysis. Due to the divergence in requirements for local waste management, the methodology serves only as a guide with recommendations to the local authorities. SWA Tools methodology provides an opportunity for unified municipal waste data collection across the European Union which allows the comparability of the given results on the local and regional level[26], [27].

The methodology defines the residual solid waste fraction as daily household and commercial waste. The methodology describes approaches toward the manual sorting and analysis of the fraction. Evaluated outputs by the SWA Tool methodology are written down [26], [27]:

- Waste Characterisation - composition
- Waste Quantification based on waste characterisation

4.1.1.1 SWA TOOL - RECOMMENDATIONS

The SWA Tool methodology is a composition of recommendations for the performance of the waste analysis. The recommendations cover the whole waste analysis process from sampling and waste characterisation to the evaluation of results. Methodology recommendations are written down. Each recommendation is assigned the name of the corresponding chapter from the methodology (written in italics) [26], [27].

1. Recommendation – *Statistical standards*: The confidence level for the expression of results is 95%. The relative accuracy of the total result shall be under 10% [27].

2. Recommendation – *Waste Characterisation – Background Information*: The methodology does not recommend collecting all data mentioned in the document. As collectable data shall be included the one important for the creation of a selection basis and which are necessary for the design of the analysis. The collection differs based on the given country and the case [27].
3. Recommendation – *Stratification*: Stratification is not obligatory for the performance of waste analysis but can provide useful additional information for waste management and rise the accuracy of results [27].
4. Recommendation – *Type of Sampling*: For the regional and local waste analysis program, if possible, the stratified random sampling method should be utilized as the basis for sample selection. Regardless of the selected strata, it is essential that the relevant waste sources for the sampling process, such as garbage bins, can be assigned and sampled according to the selected strata [27].
5. Recommendation – *Number and Type of Strata*: The methodology recommends using a maximum of five relevant strata to ensure the required accuracy of results for each stratum. Usage of a higher number of relevant strata would lead to an excessive number of necessary samples – a larger sample size – for the achievement of chosen accuracy [27].
6. Recommendation – *Level of Sampling*: The methodology recommends sampling waste from the external waste bin or container that is located outside households or business properties [27].
7. Recommendation –*Type of Sampling Unit*: The methodology recommends selecting the sampling unit depending on the volume of the waste bin. The term volume of the waste bin should not be exchanged for the volume of waste contained in the given waste bin [27].
8. Recommendation – *Type of Sampling Unit*: The recommendation is to use similar-sized sample units. Bin sizes of recommended sampling units are as follows: 120 l; 240 l; 360 l; 660 l; 1100 l; 2400 l; 3600l. In the case of analysis of units with a bin's volume lower than 120 l, the bins should be combined to form one of the mentioned sample sizes [27].
9. Recommendation – *Calculation of Overall Number of Sampling Units*: In case of knowledge of the variation coefficient of analysed waste, the coefficient can be used for calculation of the required number of sampling units according to other mathematical procedures provided by the SWA Tool document [27].
10. Recommendation – *Calculation of Overall Number of Sampling Units*: For the unknown value of the variation coefficient of the analysed waste, the suggested sample sizes for different types of waste are as follows, irrespective of the chosen sampling unit size:
    - Household waste: 45 m^3,
    - Mixture of commercial/household waste: 80 m^3,
    - Commercial waste: 100 m^3

    The values are established based on knowledge from previous waste analyses and the results of the SWA Tool Methodology [27].
11. Recommendation – *Number of Sampling Units for Individual Strata*: For each campaign, the number of sampling units for individual strata should be greater than six and the sample size should not go under 6 m^3 in bin volume for household waste. The number of minimum sampling units for individual strata for the commercial waste is fifteen and the sample size should not be less than 15 m^3 in bin volume [27].
12. Recommendation – *Generation of Random Sample Plan*: Methodology recommends generating a back-up set of random sample addresses as a part of the generation of a

random sample plan. If the identification and collection of the waste sample from the primary addresses is not possible the back-up sample plan shall be utilized [27].

13. Recommendation – *Duration of an Individual Waste Analysis Campaign*: Duration for waste sampling and collection should be a minimum of one week of waste if the municipal waste is collected daily or weekly on repeat. The duration will allow us to catch the whole working week cycle, from Monday to Friday, with its potential variation due to the absence of waste collection during the weekend [27].
14. Recommendation – *Duration of an Individual Waste Analysis Campaign*: Duration for waste sampling and sample collection should be a minimum of two weeks waste for covering the full collection cycle if the municipal waste is collected bi-weekly (fortnightly) [27].
15. Recommendation – *Collection of Samples*: The sampling units are collected by the collection team by either emptying or replacing the chosen waste bin on the regular collection interval day. For the prevention of intervention by the waste producer, the process of collection of samples should proceed without the knowledge of the waste producer [27].
16. Recommendation – *Collection of Samples*: Identification code should be attached to each collected sample. The Code should be usable in wet conditions. Necessary information about the individual sample to be completed by the collection team are [27]:
    - Exclusive identification reference code
    - Sample address
    - Collection date
    - Number and type of waste containers collected
    - Visual estimation of the filling level in% of the collected waste bins
    - Visual estimation of the filling level in% of the other waste bins at the same address with the aim of collection information for calculation of waste quantity.
17. Recommendation – *Sorting and Analysis of Samples*: The waste analysis should be implemented with the following recommendations [27]:
    - A waste analysis record sheet is assigned for each sampling unit.
    - The sample's exclusive identification code is written down into the waste analysis record sheet as the waste analysis is completed.
    - The filling level ratio in% of the waste sample bin is recorded.
    - The sampling unit's weight is recorded with an accuracy of+/- 0.1 kilograms
    - Separation of the sampling units into two initial fractions can be conducted with the aim of facilitation of the sorting process: Above 40 mm and below 40 mm, by screening with a 40 mm mesh screen (Tromel), alternatively, the sorting can proceed on the 40 mm screen table directly. This step is not mandatory and serves as a help for the sorting team.
    - Twelve compulsory primary waste categories without the "Fines" category, which are specified by the SWA Tool Catalogue, are assigned for the sorting process of the above 40 mm fraction. Each category is weighted with an accuracy of +/- of 0.1 kg. The weight is recorded for the sampling unit.
    - 10 mm mesh screen is used for screening the "below 40 mm" fraction. The screening will separate the original fraction into the following fractions: Below 10 mm; 10-40 mm.
    - The fraction "below 10 mm" is weighted with an accuracy of +/- of 0.1 kg. The weight is recorded and assigned to the "Fines" category.

- The weight is recorded for the "10-40 mm" fraction. A representative sub-sample from the fraction is created by coning and quartering. Sub sample is sorted into the primary waste categories described in the SWA Tool document. The analysed composition of the sub-sample is applied to the total weight of the 10-40 mm fraction. Calculated weights are recorded and assigned to the corresponding primary waste categories

18. Recommendation – *Sorting and Analysis of Samples*: Ideal number of persons in the sorting team according to the local situation should be based on the sorting rate of 100 kilograms of waste per 6 people per hour [27].
19. Recommendation – *Evaluation of Raw Data*: Weight results shall be transcribed from the field document to the Excel sheet. Provided Excel sheet by the SWA Tool automatically evaluates the waste composition and chosen statistical data [27].
20. Recommendation – *Quality Assurance*: Weighted stratums need to be put in the right relation. The total result is the weighted mean of the results of the one stratum [27].
21. Recommendation – *Extrapolation*: Determination of the total generated for example household residual waste can be done by multiplication of the total number of sampling units with the mean value obtained from the sample [27].
22. Recommendation – *Extrapolation*: For stratification, recommended calculation of the total output of e.g. household waste for a particular stratum should be done by multiplying the sample mean number of the stratum with the number of sampling units within the stratum. The addition of strata results leads to the calculation of the total waste amount. Calculation of the confidence interval is possible with equations available in the SWA Tool document. For stratification, the total output of e.g. household waste the total waste amount has an alternative way of evaluation with the multiplication of the weighted mean of the individual sample means with the sampling unit's total value of the researched area [27].
23. Recommendation – *Extrapolation*: Extrapolation of results should be used in cases where less than four seasonal campaigns have been realized in a seasonal analysis [27].
24. Recommendation – *Presentation of Results*: Following topics are recommended to be presented and reported [27]:
    - Raw Data is written down in an MS Excel table in the format given by the SWA Tool document.
    - Statistical calculations are written down in an MS Excel table in the format given by the SWA Tool document. An Excel template containing the formulas for the calculation is attached to the SWA Tool document. The relative confidence interval shall be included and presented as a result. An absolute confidence interval is not applicable for the comparison of results of various waste analyses due to the dependence on the corresponding mean.
    - Evaluation of single results of given stratum with a table.
    - Extrapolation of the results and waste quantification.
    - Graphical presentation of mean waste amounts of the primary waste composition categories. Recommended format of diagrams is included in the SWA Tool Document

4.1.1.2 SAMPLING STRATEGY

The first step of the physical execution of waste analysis is the collection of samples. Strategy for the sampling process is an important part of every methodology. SWA Tool methodology describes the sampling strategy as stated in recommendations 15 and 16. The aim of the strategy should be securing the representation of the aimed group with the chosen sample. The procedure of waste sampling based on the SWA Tool methodology is shown in Figure 4-1, where the sampling unit of 1 m^3 is represented by four 240 L containers [27]:

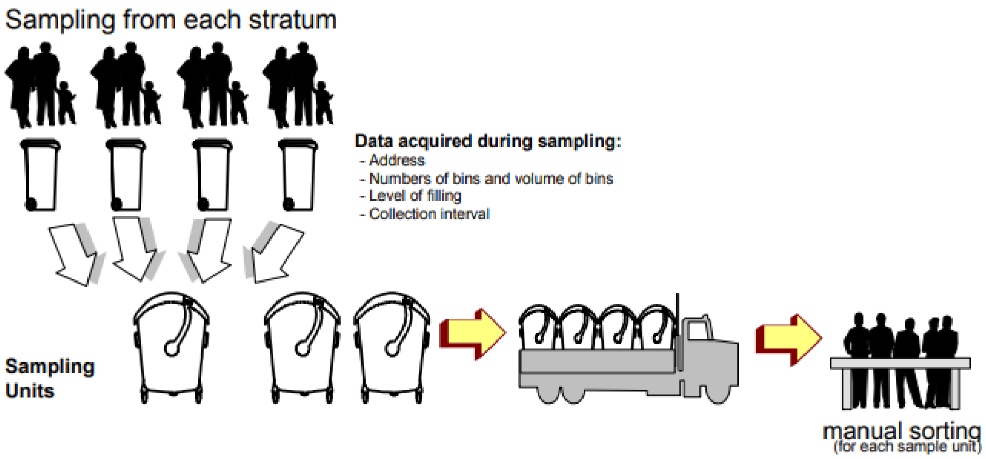

Figure 4-1 Waste Sampling by the SWA Tool Methodology [27]

During the sampling process, collected waste samples from chosen area shall not be mixed with other samples due to the clarity of results. Collected sampling units are analysed according to the sorting process as discussed in the following sub-sections[27].

4.1.1.3 SORTING TECHNIQUE

Representative waste samples are sorted and analysed concerning the methodology. SWA Tool methodology describes the sorting and analysis technique with recommendations 17 and 18. A record sheet is assigned for each waste sample. In the first step, the waste sample's weight is recorded. With the usage of the 40 mm mesh screen, the waste sample is separated into two fractions – above and below 40 mm. Screening is executed on the below 40 mm fraction with the 10 mm mesh screen. The weights of the under 10 mm and the 10-40 mm fraction are recorded. The weighted 10-40 mm fraction is coned and quartered to obtain the representative sub-sample. The representative sub-sample of the 10-40 mm fraction and the above 40 mm fraction are manually sorted into categories given by the SWA Tool Sorting Catalogue. The weight of each waste composition category is recorded. The sorting technique is shown in Figure 4-2 [27]:

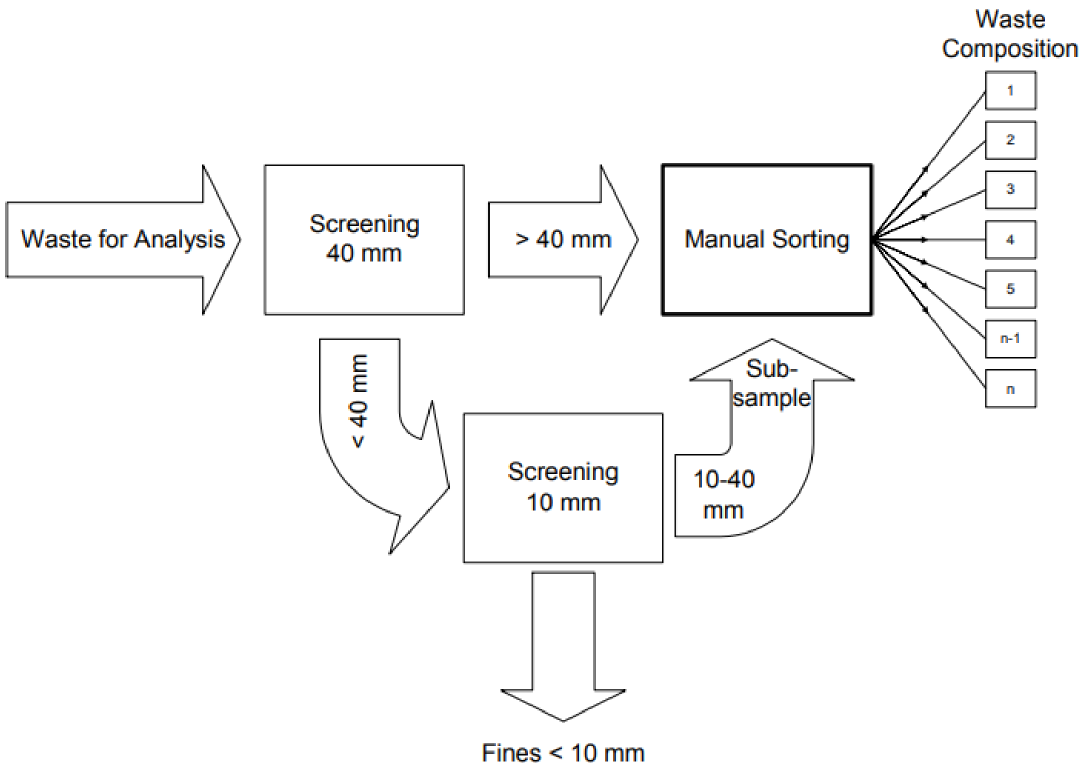

Figure 4-2 Sorting technique by the SWA Tool Methodology [27]

The sorting and analysis process allows to find out the waste composition of the given sample. The SWA Tool Sorting Catalogue introduces 13 compulsory primary categories and 35 recommended secondary categories. The sorting process generates the raw data for the evaluation process of waste analysis [27].

4.1.2 Certified Czech methodology - TIRSMZP719

The waste composition analysis methodology used for this master thesis was established as a part of a national project utilized by the institute of process engineering at the Brno University of Technology. The methodology aims to obtain a national tool comparable to similar tools for monitoring the composition of municipal solid waste across the European Union countries. Certified methodology secures stability and unification of the data obtained during field research in various locations and by different persons. The methodology presents a procedure for obtaining the municipal solid waste composition. The results of the methodology are usable for waste management at the level of national planning. The determination of the aim and the programme is a critical point for the precision of the methodology procedure [26], [28].

4.1.2.1 Methodology background

The SWA Tool serves as a background for the Czech methodology. The Czech methodology is in accordance with the recommendations given by the SWA Tool and expands the recommendations with the gathered field experience and requirements from the local authorities. During the formation of the Czech methodology, the main followed recommendations from the SWA Tool were [26], [28]:

- Recommendation num. 4 - *Type of Sampling*

- Recommendation num. 5 - *Number and Type of Strata*
- Recommendation num. 6 - *Level of Sampling*
- Recommendation num. 8 - *Type of Sampling Unit*
- Recommendation num. 11 - *Number of Sampling Units for Individual Strata*
- Recommendation num. 13.14 - *Duration of an Individual Waste Analysis Campaign*

A detailed description of the recommendations can be found in the previous chapter. In addition to the SWA Tool, the following legislative documents and standards were used:

- Act no. 541/2020 Coll. - Waste
- Act no. 477/2001 Coll. - Packaging and amending certain acts
- Regulation no. 8/2021 Coll. - Waste catalogue and waste characterisation
- Regulation no. 273/2021 Coll. - Details of waste management
- 6. Methodological Guideline concerning the waste sampling
- EN 14899 – Characterisation of the waste - Sampling of waste materials - Framework for the preparation and application of a Sampling Plan
- CEN/TR 15310-2 - Characterization of waste - Sampling of waste materials - Part 2: Guidance on sampling techniques
- UNE CEN/TR 15310-5 - Characterization of waste - Sampling of waste materials - Part 5: Guidance on the process of defining the sampling plan
- ISO 3534-1 - Statistics — Vocabulary and symbols — Part 1: General statistical terms and terms used in probability

The methodology provides a tool for statistical processing and results interpretation. The tool draws from basic knowledge of descriptive statistics. The methodology shall be used for monitoring the composition of the municipal solid waste and municipal waste [26], [28].

4.1.2.2 SAMPLING STRATEGY

The sampling strategy of the Czech methodology is comparable to the strategy established by the SWA Tool. The methodology acknowledges any waste bin, container or another type of waste holder arranged by the municipality as a sampling device or sampler. The representative sample is obtained by usage of sampling devices with a volume of 1 m^3 corresponding to the container's volume of 1,100 litres. The representative sample can be obtained by mixing smaller samples from containers of smaller volume, which together form the required volume of 1,100 litres. The methodology does not recommend sampling of treated waste for example by the waste compactor during the waste collection process. 10 representative samples are the recommended amount with the repetition of 4 times per year for the sampling programme to determine the annual average composition of the municipal solid waste. The monitored indicator is the mass of the municipal solid waste fractions contained in the representative sample. The methodology provides for 3 sorting levels, with the material composition or original purpose of the item before it became waste serving to distinguish the specified fractions at each level. The methodology provides detailed descriptions of the fractions and sorting levels [26], [28].

4.1.2.3 SAMPLE'S IMPORTANT INFORMATION

For accurate waste composition analysis, it is necessary to secure and provide the following information connected to the representative sample [26], [28]:

- Unique ID of the sample
- Information about the place from where the sample was obtained
- Date of sampling, starting time of sorting
- Amount of the same bins in the collection area – estimation of bin's filling in the percentage
- Weight of the sample
- Photo documentation of the sorted fractions

As a part of the waste composition analysis process, the protocol for the results of the analysis of the sample shall be utilized. Detailed information about the obligatory documents and protocols is provided as a part of the methodology TIRSMZP719 [26], [28].

4.1.2.4 SORTING TECHNIQUE

Since the Czech methodology follows the recommendations given by the SWA Tool, the procedure of the analysis of the sample is similar to the procedure of the SWA Tool Methodology, described in Chapter 4.1.1.3 [26], [28].

The waste becomes a sample in the moment of spilling out of the waste container onto the screen. Depending on the size of the screen, the sample can be spilt out piecewise or as a whole. The methodology suggests the usage of screens with the following sizes depending on the aim of the assessment [26], [28]:

- 40x40 mm mesh size
- 20x20 mm mesh size
- 10x10 mm mesh size

The usage of a screen with a given size allows the division of the fine fraction. The sample located on the screen is separated into the fractions established by the methodology. A separate container is assigned for each fraction. Weight in kilograms of the sorted fractions shall be recorded. Due to their size, electronic devices and batteries can occur in the fine fraction and shall be separated into their given fraction before the determination of the weight of the fine fraction. A practical example of the procedure is shown in Figure 4-3 [26], [28]:

Figure 4-3 Procedure of the analysis by the Czech methodology [26]

5 METHOD

The purpose of the practical part is to present procedures connected to the waste composition analysis. Waste composition analysis is a methodology which enables further studies necessary for waste treatment and waste management. Throughout the practical part, the collected data sets are used to show trends in selected waste categories. Trends and discoveries based on the waste composition analysis datasets will allow proposing of possible solutions for waste management. In the practical part, a tool for data analysis of municipal solid waste is developed. The tool is applied to assess selected waste streams, which are subsequently divided into individual fractions. The fractions and their characteristics change over time, providing specific information about each waste stream, which are important for decisions related to waste recovery. Table 5-1 introduces studied waste streams and their fractions on three levels [28], [29].

<table>
<tr><th>1. level</th><th>2. level</th><th>3. level</th><th>1. level</th><th>2. level</th><th>3. level</th></tr>
<tr><td rowspan="5">Paper</td><td rowspan="2">Packaging</td><td>Cardboard</td><td rowspan="4">Bio</td><td rowspan="3">Kitchen</td><td>Fruit and vegetable</td></tr>
<tr><td>other - packaging paper</td><td>Residues from the preparation of fruit and vegetable</td></tr>
<tr><td rowspan="2">Non Packaging</td><td>Magazines</td><td>other food</td></tr>
<tr><td>newspaper and office paper</td><td>Garden</td><td>Garden Bio</td></tr>
<tr><td>Other</td><td>other paper 3 category</td><td>Wood</td><td></td><td>Wood 3 level</td></tr>
<tr><td rowspan="7">Plastic</td><td rowspan="6">Packaging</td><td>Wraps/bags</td><td rowspan="2">Glass</td><td>Packaging</td><td>Packaging Glass 3 level</td></tr>
<tr><td>hard plastic</td><td>Non Packaging</td><td>Non packaging glass 3 level</td></tr>
<tr><td>Transparent PET</td><td rowspan="5">Metal</td><td rowspan="3">Packaging</td><td>Ferromagnetic</td></tr>
<tr><td>Coloured PET</td><td>Aluminium</td></tr>
<tr><td>PS</td><td>Other packaging metals</td></tr>
<tr><td>Other packaging plastic</td><td rowspan="2">Non Packaging</td><td>Ferromagnetic non packaging</td></tr>
<tr><td>Non Packaging</td><td>non packaging plastic</td><td>other non packaging metals</td></tr>
</table>

Table 5-1 Studied municipal solid waste streams

5.1 DATA COLLECTION

It is necessary first to gather data to give suggestions and propositions connected to municipal waste recovery. Czech methodology of waste composition analysis collects data through individual manual sorting procedures due to economic, logistics and time reasons [28].

The selection of the examined sample is based on the stratification procedure. Stratification gains the representative data by redistribution of the target area into the smaller representative groups – stratification layers. Data for each representative group is obtained proportionally with respect towards its ratio in the total amount of the given sample. Stratification is the first step for statistical planning and calculation with measured data in the waste composition analysis [28].

For the sorting procedure, the given sample is placed on the sieve. The sieve with a 40 to 10 mm mesh size is used. The size of the sieve allows a thorough examination of the oversize waste fraction [28].

The given sample is sorted into individual waste categories. Categories are based on the 3 sorting levels of classification. The first sorting level of waste composition identifies the following categories researched throughout the municipal solid waste [28]:

- Paper and board and cardboard
- Plastic
- Biodegradable waste
- Wood
- Glass
- Metals
- Textile
- Composite packaging and tetra pack
- Electronic devices
- Batteries
- Other waste
- Fine proportion

The first sorting level introduces the most general waste streams. Each following sorting level creates higher diversity into categories of previous by distinguishing more accurate categories. The first sorting level is a prerequisite for the second and third levels. The sorting level is determined by the decision of the contracting authority. In the practical part of the master thesis, the first and third level (Section 5.3) of waste composition analysis is studied [28].

5.2 DATA MANAGEMENT

The gathered data through the stratification sampling is written down and sorted in Microsoft Excel. Each sample is written down with information about the weight of the sample, the place, the date, and the level of sampling. Pieces of information about the data collection process secure individual recognition of given samples. The time and location stamps are important information for the practical part of the master thesis.

The aim of the data management in the waste composition analysis of this master thesis is to see possible differences, changes, and trends in municipal solid waste categories during the given time stamp. The available dataset is composed of 621 waste composition records.

The challenge with a such big amount of data comes with filtration and prioritization of each sample. These challenges are processed with the use of Microsoft Visual Basic for Application (VBA). The VBA allows easier manipulation of the given dataset for the third-party member, quicker and easier changes in future research through the given dataset and ensures automation of possible additional inputs of samples.

Filtration of the dataset for the practical part of the master thesis is based on the time sample of the given data. Samples are gathered depending on the data's collection month and year. The next step is to summarize/unite the filtered data of the selected month and year into one value for each category. As mentioned before, each sample during the sorting process can have a different weight. To be in respect to this phenomenon, the formula for the weighted arithmetic mean value $\bar{X}_{mean}$ (5.1) shall be used.

$$\bar{X} = \frac{\sum_{i=1}^{n} w_i \cdot x_i}{\sum_{i=1}^{n} w_i} \tag{5.1}$$

Where w_i represents the total weight of the given sample in kg, x_i represents the partial amount of the waste in the chosen category in the percentage of the total amount, $\bar{X}$ represents the weighted arithmetic mean value of the chosen category during the chosen time in percentage of the total amount.

The 3-sorting level hierarchy creates a problem for the equation of the weighted arithmetic mean value (5.1). For example, the data collection is provided only with the first level of waste composition. A sample is put into the database with non-zero values for the first sorting level - $x_{i.1.level} \neq 0$. Values in the second and third levels are zero - $x_{i.3.level} = 0$. A problem occurs if the weighted arithmetic mean value at the third level $\bar{X}_{3.level}$ is calculated. The sum of weights $\sum_{i=1}^{n} w_{i-3.level}$ in the denominator includes value attributable to the first sorting level. The final value of the arithmetic mean value at the third level $\bar{X}_{3.level}$ in chosen category is affected by a sample for which the third sorting level is not produced.

Prevention for the mentioned problem is a modification of equation (5.1) into the following equation (5.2).

$$\bar{X}_{mean} = \frac{\sum_{i=1}^{n} w_i \cdot x_i}{\sum_{i=1}^{n} w_i \cdot s_i} \tag{5.2}$$

$$s_i = \sum_{i=1}^{n} x_i \tag{5.3}$$

The denominator is the sum of multiplications of the sample's total weight w_i and the sum s_i of categories partial amounts at the chosen level. Equation (5.3) shows the problem's solution. The sum s_i obtains only values $s_i = 1$, if the sampling procedure for the given level was executed, and $s_i = 0$ in the opposite way. The sum s_i allows calculation with different sorting levels established by the data collection process. Equation (5.2) is used in the following chapter when programming a script within a procedure called Calculate().

5.2.1 VISUAL BASIC FOR APPLICATIONS (VBA) CODE

As previously mentioned, for the data management was used programming language Visual Basic for Applications (VBA) available for the Microsoft Office package. For the master thesis, the data management is carried out on the first and third levels of the waste composition analysis. The Excel file contains separate sheets with results for both researched levels. The programmed scripts allow the user to filter and recalculate data with the following terms:

- Date – Year and Month
- Location
- Combination of both conditions

At the start, the user chooses from mentioned terms the aim of the filtration. The first filtration from the raw dataset is processed through the Advanced Filter function, which based on the user's choices finds and copies data from the general dataset to the allocated sheet. This process is done in a sub Filtration(). Sub is a VBA procedure which can perform a set of tasks defined inside the procedure. The sub Filtration() is shown in Figure 5-1.

```
Sub Filtration()


    ThisWorkbook.Worksheets("pes").Range("B5:CT700").Clear
    'clear the cell

    Dim RgData As Range, rgCriteria As Range, rgOutput As Range

    Set RgData = ThisWorkbook.Worksheets("DATA").Range("A9:CS700")
    Set rgCriteria = ThisWorkbook.Worksheets("DATA").Range("A1").CurrentRegion
    Set rgOutput = ThisWorkbook.Worksheets("pes").Range("B5")

    RgData.AdvancedFilter xlFilterCopy, rgCriteria, rgOutput


End Sub
```

Figure 5-1 Sub Filtration()

The second step is for the filtered data to be consolidated and recalculated into the weighted arithmetic mean value $\bar{X}_{mean}$ (4.2) specified in the previous chapter. The arithmetic mean value of each fraction in the given researched level is written down into the appropriate sheet with the chosen time stamp specification. Programmed script for the second step in a sub Calculate() performs the following tasks:

- Detection of a free row in the sheet for the first and third levels of the waste analysis
- Copy and notation of researched dateline
- Calculation of arithmetic mean value of given fraction based on equation (5.2)
- Writing down the calculated values into the sheet based on the level of the analysis

To enable calculation for all categories, the calculation process is looped by the "for" function. The main part of the script of sub Calculate() is shown in Figure 5-2.

```
sumec = f.Range("CS1").Offset(5).Resize(NumOfCol - 5)

'Need to control if the sum is 0 then write only 0
sum3uroven = WorksheetFunction.Sum(sumec)

If sum3uroven = 0 Then

    For j = help To untilWhen

        b.Cells(NumOfLine, j).Value = 0
   'write only 0

    Next j
    Else


    For j = help To untilWhen '3. level of calculation

        b.Cells(NumOfLine, j).Value = WorksheetFunction.SumProduct(f.Range(f.Cells(6, i), f.Cells(NumOfCol, i)), _
        f.Range(f.Cells(6, 6), f.Cells(NumOfCol, 6))) / _
        WorksheetFunction.SumProduct(f.Range(f.Cells(6, 6), f.Cells(NumOfCol, 6)), _
        f.Range(f.Cells(6, SloupecSuma3uroven), f.Cells(NumOfCol, SloupecSuma3uroven)))
        'zapis do cely o sloupci J a cislu radku hodnotu vazeneho prumeru, ktery je pocitany z icka=czech
        'calculation formula
        i = i + 1
        'Step to next category
    Next j
End If


For j_1 = help_1 To untilWhen_1 '1. level of calculation

    c.Cells(NumOfLine_1, j_1).Value = WorksheetFunction.SumProduct(f.Range(f.Cells(6, i_1), f.Cells(NumOfCol, i_1)), _
    f.Range(f.Cells(6, 6), f.Cells(NumOfCol, 6))) / _
    WorksheetFunction.Sum(f.Range(f.Cells(6, 6), f.Cells(NumOfCol, 6)))
    'zapis do cely o sloupci J a cislu radku hodnotu vazeneho prumeru, ktery je pocitany z icka=CZECH
    'calculation formula
    i_1 = i_1 + 1
    'Step to next category


Next j_1
```

Figure 5-2 Part of the sub Calculate()

To provide quick availability of the results and automatization of the filtration and calculation process, described steps are afterwards looped with the "for" functions. In the sub loopme() the first for loop is designed for the number of years in which the analysis has taken place. The script works with a dynamic range of year values established in the raw dataset, therefore the programmed script is optimized for new data deposits. The dynamic range is created using the function "XLDOWN". Second for loop is designed for the number of months. In the second loop, the script uses the if function to check whether the waste composition analysis has been carried out in the given month. The loop ends when the calculation reaches the end of the timeline from the raw data. The sub loopme() is shown in Figure 5-3.

```
Sub loopme()
Dim i As Long
Dim j As Long
Dim yearAvailable As Range
Dim yearList As Variant
Dim year As Variant
Dim yearFirst As Range
Dim yearLast As Range

Set yearFirst = ThisWorkbook.Worksheets("DATA").Range("D10")
Set yearLast = yearFirst.End(xlDown)
Set yearAvailable = ThisWorkbook.Worksheets("DATA").Range(yearFirst, yearLast)
 yearList = WorksheetFunction.Unique(yearAvailable)
'find years from the raw data
ThisWorkbook.Worksheets("1. uroven data").Range("A3:R21").Clear
ThisWorkbook.Worksheets("3. uroven data").Range("A5:AR21").Clear
'Clear cells in my sheets'
For Each year In yearList ' going through all years

     ThisWorkbook.Worksheets("DATA").Range("D2") = year
     'write down the year for the filter function
            For i = 1 To 12 'going through all months
                ThisWorkbook.Worksheets("DATA").Range("H2") = i
                'write down the month
                Call Filtration
                'use filter function
                If ThisWorkbook.Worksheets("pes").Range("K6").Value = "" Then
                GoTo pejsek
                'jump to new month if the month is blank
                Else
                Call Recalculate
                'use calculation and writing down function

                End If

pejsek: 'Jump if the month is blank
            Next i
Next year
Call CopyFormat
'copy format
End Sub
```

Figure 5-3 Sub loopme()

To maintain the set design of the tables for the first and third levels of solid waste analysis, the respective styles of each fraction are assigned to the filtered and recalculated data with a separate Sub CopyFormat(), which is shown in Figure 5-4.

```
Sub CopyFormat()

    Dim a As Worksheet
    Dim b As Worksheet
    Dim c As Worksheet

    Dim kopirovanemisto_1 As Range
    Dim kopirovanemisto_2 As Range
    Dim kamkopiruji_1 As Range
    Dim kamkopiruji_2 As Range


    Set a = Sheets("obce")
    Set b = Sheets("3. uroven data")
    Set c = Sheets("1. uroven data")

    Set kopirovanemisto_1 = a.Range("B2:S2")
    Set kopirovanemisto_2 = a.Range("B3:AS3")

    Set kamkopiruji_1 = c.Range("A3:R25")
    Set kamkopiruji_2 = b.Range("A5:AR27")

    kopirovanemisto_1.Copy
    kamkopiruji_1.PasteSpecial xlPasteFormats
    'copy from sheet "obce" to "1. uroven" the style
    Application.CutCopyMode = False

    kopirovanemisto_2.Copy
    kamkopiruji_2.PasteSpecial xlPasteFormats
    'copy from sheet "obce" to "3. uroven" the style
    Application.CutCopyMode = False


End Sub
```

Figure 5-4 Sub CopyFormat()

To provide accurate data for the locations, where the analysis has taken place a special script sub Filter_location() has been programmed. The sub loads into respective variables the unique locations. The variable is used as the header, which defines the for-loop iteration cycle. In the body of the iteration cycle, the variable containing the location is written down into a respective cell in a sheet “DATA”. With a variable written down, the sub loopme() is used for the filtration and calculation over the whole timeline. For each location, a new sheet is created. The sheet contains the results of the first level of analysis and diagrams of researched fractions. The script does not generate a diagram for each fraction only copies diagrams from the sheet, where the results are originally generated. The loop ends when results are generated for all unique locations. The sub is shown in the figure 5-5.

```
Sub Filter_location()

Dim pomoc As Integer
Dim lokace As Variant
Dim seznam_lokaci As Variant
Dim ws As Worksheet
Dim ws1 As Worksheet


seznam_lokaci = ThisWorkbook.Worksheets("obce").Range("E7").CurrentRegion
'Take the unique location
For Each lokace In seznam_lokaci
    ThisWorkbook.Worksheets("1. uroven data").Range("A3:R21").Clear
    ThisWorkbook.Worksheets("3. uroven data").Range("A5:AR21").Clear
    'clearing of cell
    ThisWorkbook.Worksheets("DATA").Range("F2").Value = lokace
    'writing location into the cell from where the filtration is executed
    Call loopme
    'do same procedure as for general SWA
    Set ws1 = ThisWorkbook.Worksheets("1. uroven data")
    Set ws = ThisWorkbook.Worksheets.Add(After:=ThisWorkbook.Worksheets(ThisWorkbook.Worksheets.Count))
    ws.Name = lokace & " 1. uroven"
    ws1.Cells.Copy Destination:=ws.Cells
    'Creating a new excel sheet for each location
Next lokace

ThisWorkbook.Worksheets("DATA").Range("F2").Value = ""
'leaving the searching cell empty
End Sub
```

Figure 5-5 Sub Filter_location()

Figure 5-6 shows the relation between introduced procedures and their purpose.

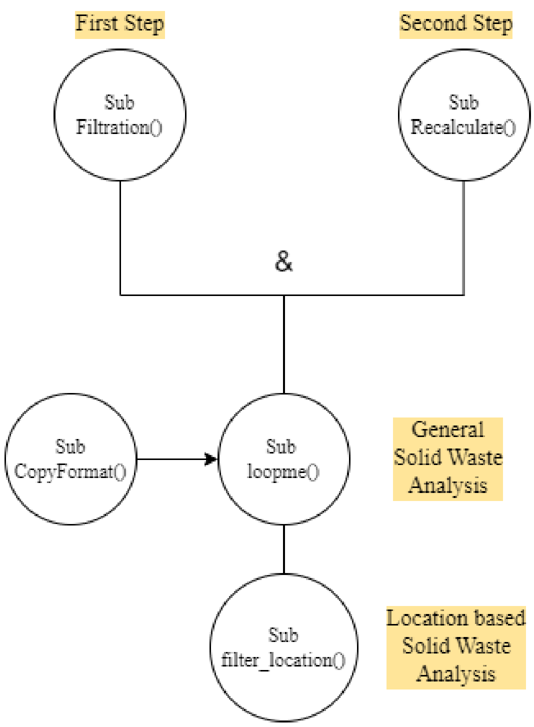

Figure 5-6 Relation between procedures

5.3 CHANGES IN THE MUNICIPAL SOLID WASTE COMPOSITION

Waste composition analysis allows monitoring of changes and possible trends throughout the examined municipal solid waste. Data collection serves for gathering the initial raw data, the data management uses the raw data set and prepares it in such a way that the goals set by the client or in this case by the thesis can be achieved. The changes in chosen municipal solid waste categories are followed in relation to the time change. The relation establishes patterns in the given streams. Monitored streams and their levels:

- Paper – First and third level
- Plastic - First and third level
- Biodegradable waste - First and third level
- Wood – First level
- Glass - First and third level
- Metal - First and third level

Different levels of waste composition analysis bring different types and results of the analysis. The third level allows a closer look at the composition of the stream studied in the first level with the definition of fractions appearing in the stream. Information about shown fractions in the third level is valuable for decision-making in waste recovery problematic. The connection between levels and categories is described at the start of chapter 4 and in the following chapters dealing with the third level of waste composition analysis. The methodology does not recognize any other fractions of the wood waste stream after the first level, therefore the analysis results are the same in the first and third levels for the wood waste stream. Figure 5-7 shows a reference diagram for the waste composition analysis at the first and third levels of municipal solid waste [28].

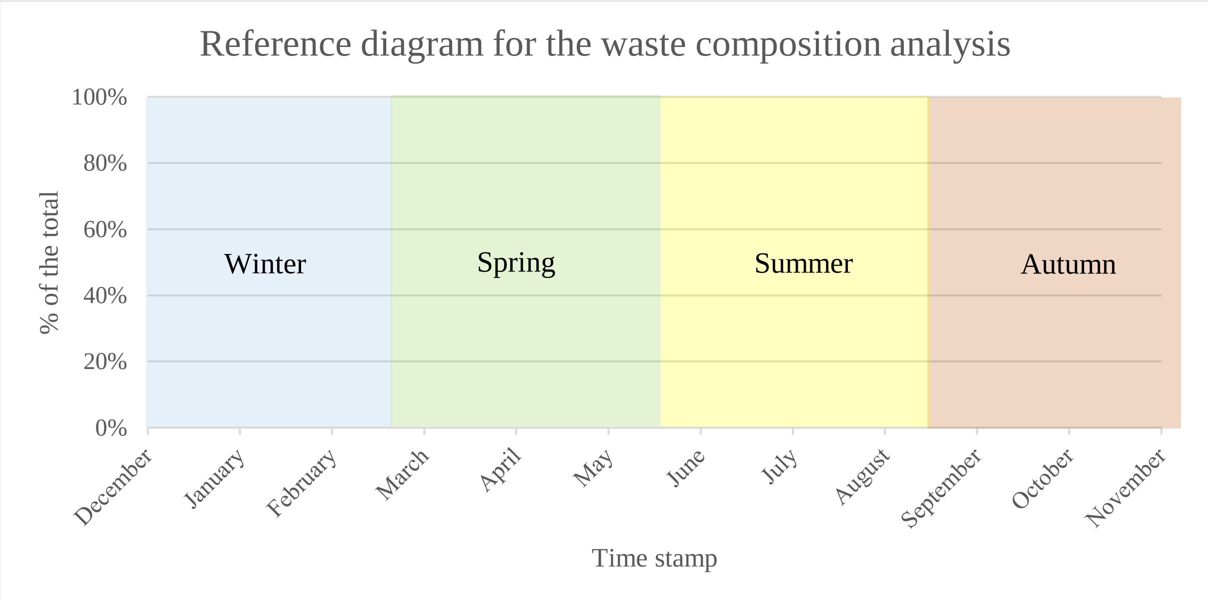

Figure 5-7 Reference diagram

5.3.1 MUNICIPAL SOLID WASTE COMPOSITION ANALYSIS IN THE FIRST LEVEL

The following charts hold the time value on the x-axis and the percentage value of the chosen category in the total amount of the sample on the y-axis. The values on the x-axis stay unchanged in the shown charts. The scale on the y-axis is the same for all categories except the biodegradable category. Due to the amount of biodegradable waste fraction in comparison with the other researched fractions the scale of the y-axis for the biodegradable waste needs to be adjusted. Table 5-2 shows the average amounts per month of followed waste streams. The table does not include the values of all waste streams introduced in Chapter 5.1. The average values of the non-studied waste streams in the first level are available in Figure 5-14.

Year/Month	Paper	Plastic	Bio	Wood - treated	Glass	Metals
2019/08	9.22%	12.25%	22.55%	1.04%	4.55%	2.24%
2019/09	6.17%	5.97%	30.63%	1.69%	2.66%	1.72%
2019/10	4.44%	3.00%	59.55%	0.29%	1.38%	3.57%
2019/11	8.22%	6.98%	26.45%	0.58%	3.36%	1.84%
2019/12	9.67%	7.20%	23.92%	0.97%	2.20%	1.67%
2020/01	2.89%	3.50%	24.20%	0.17%	1.96%	1.71%
2020/02	7.03%	9.11%	21.77%	0.97%	3.69%	1.71%
2020/03	5.14%	4.26%	24.28%	1.22%	2.50%	1.64%
2021/08	9.43%	8.49%	34.71%	0.88%	3.93%	1.76%
2021/09	6.24%	8.39%	37.07%	0.69%	3.71%	3.15%
2021/10	5.08%	6.70%	32.28%	0.39%	3.18%	1.82%
2021/11	7.62%	7.44%	26.15%	0.56%	4.82%	2.76%
2021/12	7.14%	6.34%	26.69%	0.38%	3.44%	1.57%
2022/01	5.09%	6.23%	28.62%	0.01%	3.71%	2.79%
2022/02	5.97%	6.26%	29.83%	0.10%	2.23%	1.99%
2022/03	9.24%	10.11%	30.62%	1.87%	2.54%	1.90%
2022/04	3.00%	5.39%	29.04%	0.36%	3.35%	2.10%
2022/05	4.85%	6.10%	28.59%	0.61%	3.35%	2.21%
2022/06	6.98%	7.01%	31.38%	0.02%	3.27%	1.98%

Table 5-2 Results of analysis for chosen streams

Paper stream changes dependent on the time values are shown in the following chart:

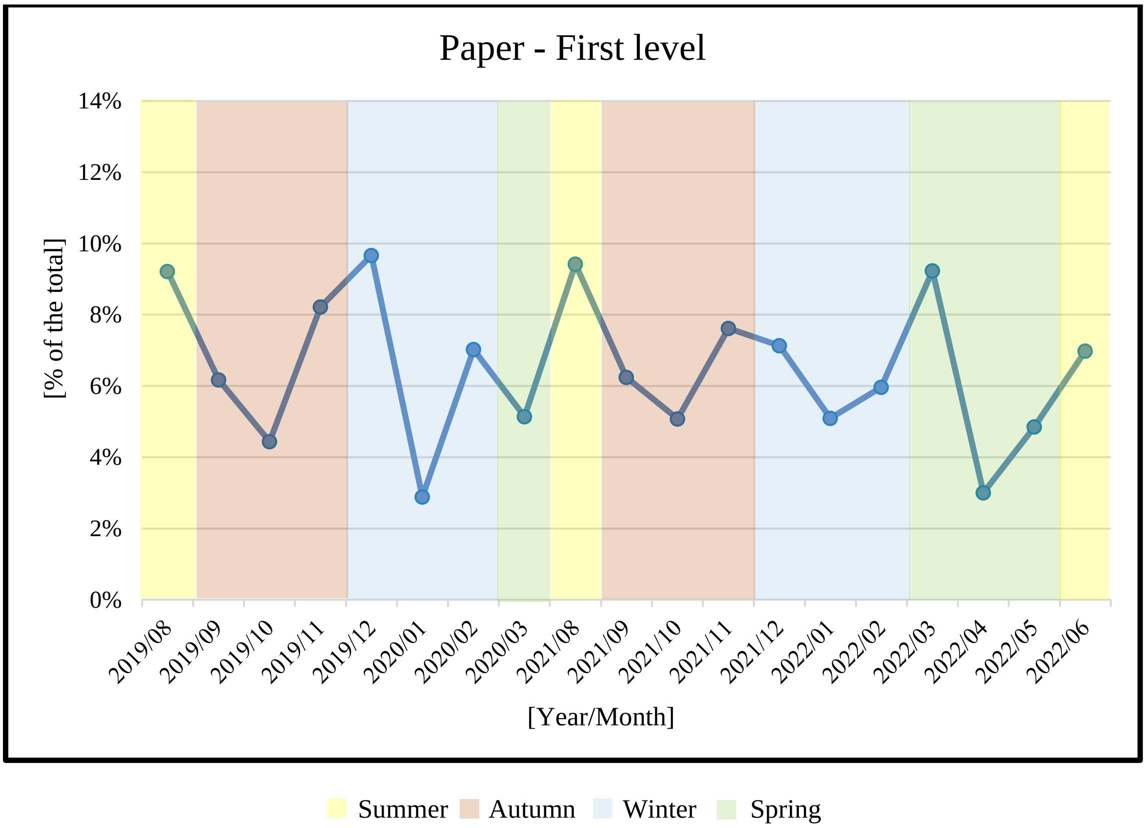

Figure 5-8 Paper stream changes 1. level

Figure 5-8 and Table 5-2 show that municipal solid waste generally holds during the calendar year around 3 to 9% of the paper fraction. The maximum mean value of the paper stream was recorded in December 2019 with $\bar{X}_{Paper,mean,max}$ = 9.67%. The lowest mean value was recorded in January 2020 with $\bar{X}_{Paper,mean,min}$ = 2.89%. The average paper stream mean value through the whole dataset is $\bar{X}_{Paper,mean,avrg}$ = 6.49%.

The trend in the paper stream could be seen around the summer months where the paper stream stands for more than 8% in August 2019 and 2021 and the rising trend is visible in May and June 2022. The high differences between certain months can be explained by the location of the data collection. In smaller villages, the paper stream is often used as a source of heating for home chimneys. The overall low value can be explained by established paper waste separation through a special paper bin.

Plastic stream changes during the given timeline are described in the following chart:

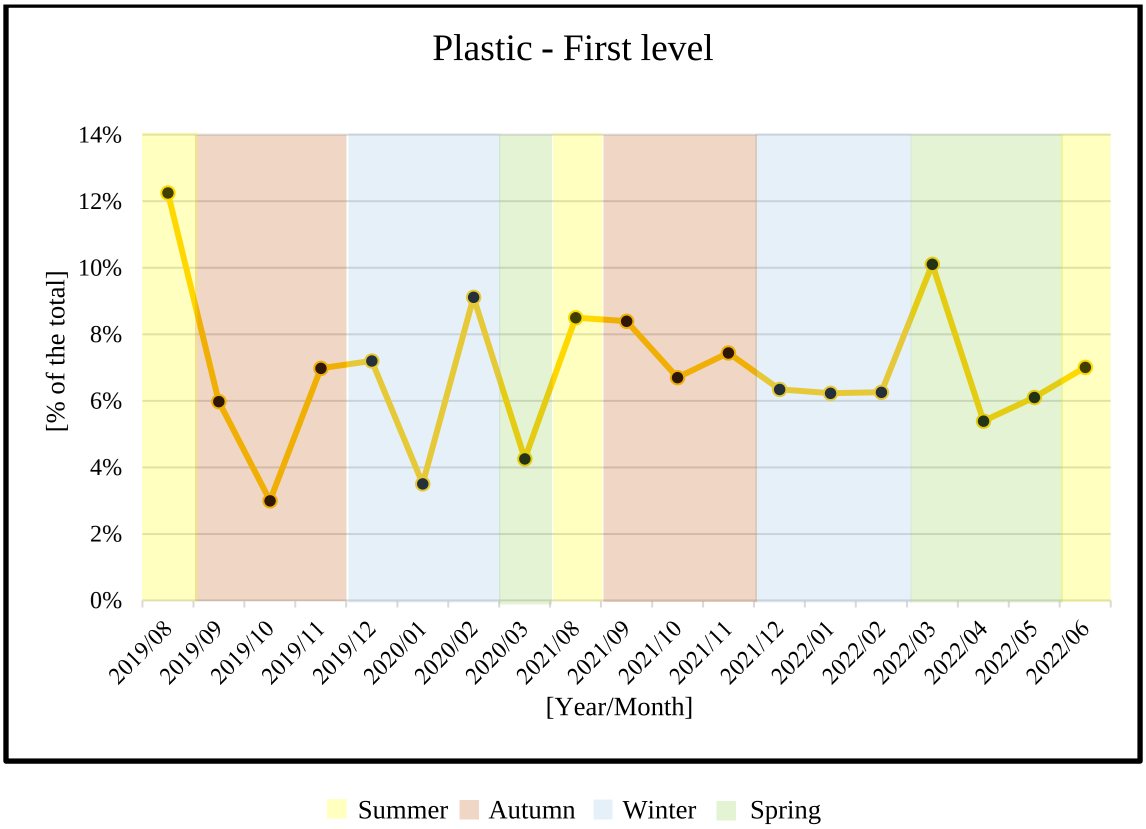

Figure 5-9 Plastic stream changes 1. level

Figure 5-9 and Table 5-2 show that municipal solid waste generally holds during the calendar year around 4 to 10% of the plastic stream. The maximum mean value of the plastic stream was recorded in August 2019 with $\bar{X}_{Plastic,mean,max}$ = 12.25%. The lowest mean value was recorded in October 2019 with $\bar{X}_{Plastic,mean,min}$ = 3%. The average plastic stream mean value through the whole dataset is $\bar{X}_{Plastic,mean,avrg}$ = 6.88%.

In figure 5-9, the years 2019 and 2020 report significant changes in results between individual steps. The plastic stream holds a similar value of around 6 to 7% during the years 2021 and 2022 with a deflection/deviation in March 2022 with $\bar{X}_{Plastic,mean,March}$= 10.11%.

Biodegradable waste stream development based on a given time is described through the following chart:

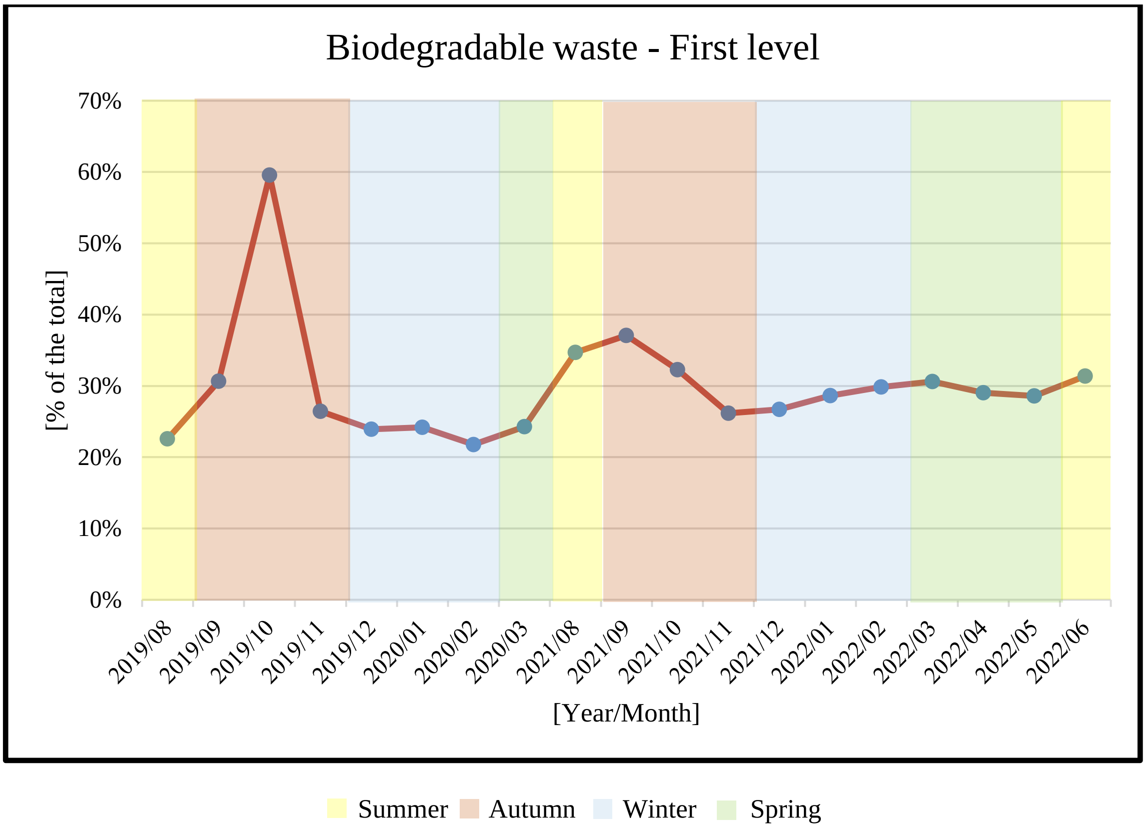

Figure 5-10 Biodegradable waste stream changes 1. level

Figure 5-10 and table 5-2 show the amount of biodegradable waste in municipal solid waste with the value on average around 20 to 40%. The maximum mean value of the biodegradable waste stream was recorded in October 2019 with $\bar{X}_{Bio,mean,max}$ = 59.55%. The lowest mean value was recorded in February 2020 with $\bar{X}_{Bio,mean,min}$ = 21.77%. The average biodegradable waste stream mean value through the whole dataset is $\bar{X}_{Bio,mean,avrg}$ = 29.91%.

Figure 5-10 is revealing the high value of the biodegradable waste stream in municipal solid waste. The deviation in October 2019 can be explained by the specificity of the sampling location in the data collection process. Certain sites are more prone to biodegradable waste generation than others. As an example, municipalities with rural households are likely to generate more biodegradable waste compared to cities with dense populations due to the high value of biowaste from the garden. The start of autumn – September, October shows a trend of the value increase.

Wood stream changes during the time stamp are described in the following chart:

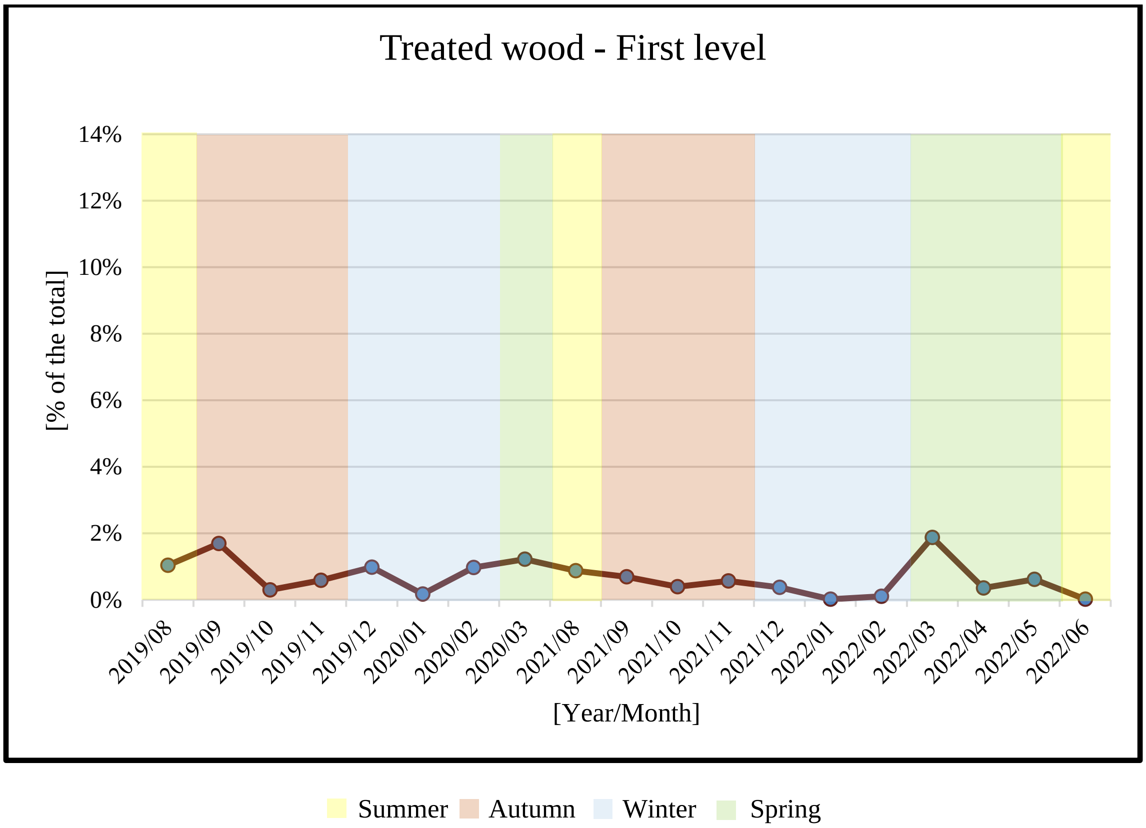

Figure 5-11 Wood stream changes 1. level

Figures 5-11 and Table 5-2 show the amount of treated wood in municipal solid waste with a small value of around 1%. The maximum mean value of the treated wood stream was recorded in March 2022 with $\bar{X}_{wood,mean,max}$ = 1.87%. The lowest mean value was recorded in January 2022 with $\bar{X}_{wood,mean,min}$ = 0.01%. The average wood stream mean value through the whole dataset is $\bar{X}_{wood,mean,avrg}$ = 0.67%.

During the following time, the wood waste does not exceed the value of 2% in municipal solid waste. Based on the data, March is a month with a rising trend of generated wood waste.

Glass stream progress based on the given timeline is described through the following chart:

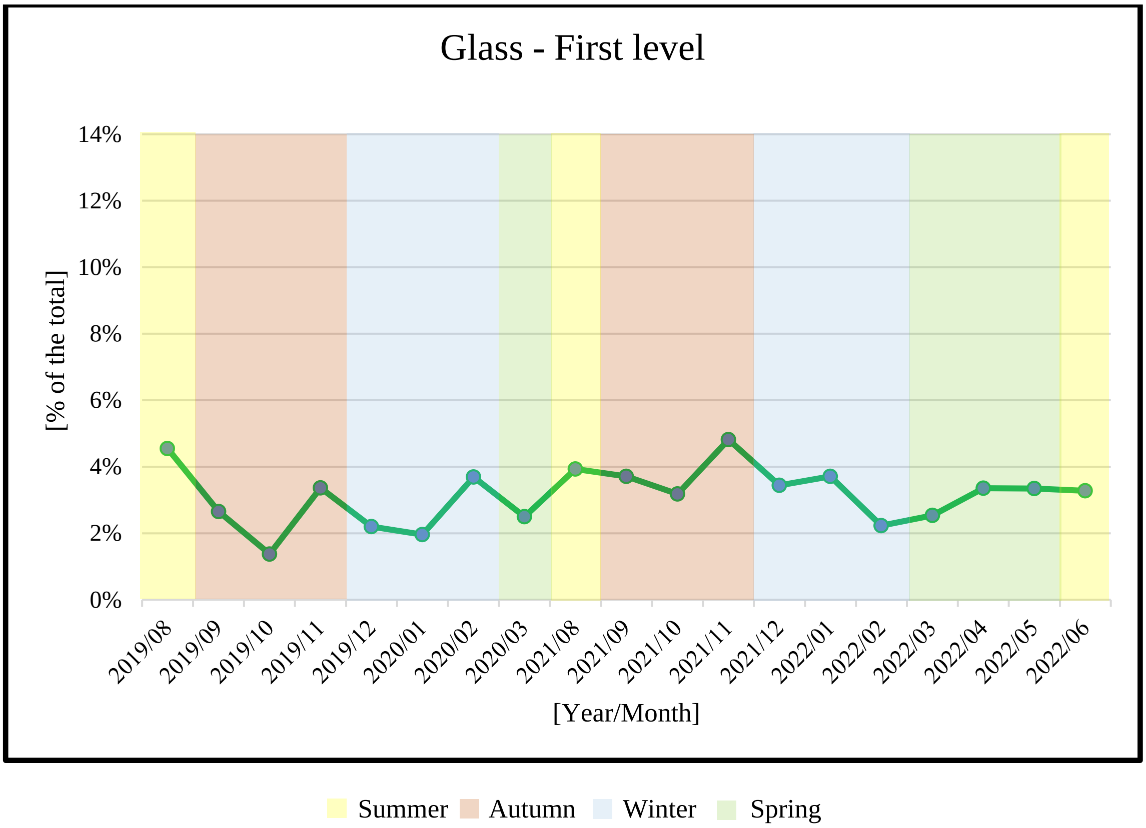

Figure 5-12 Glass stream changes 1. Level

Figure 5-12 and Table 5-2 show the amount of glass stream in municipal solid waste with a value between 1 and 5%. The maximum mean value of the glass stream was recorded in November 2021 with $\bar{X}_{glass,mean,max}$ = 4.82%. The lowest mean value was recorded in October 2019 with $\bar{X}_{glass,mean,min}$ = 1.38%. The average glass stream mean value through the whole dataset is $\bar{X}_{glass,mean,avrg}$ = 3.15%.

Figure 5-12 shows a rise in the glass stream in municipal solid waste in November 2019 and 2021. Datasets from the years 2019 and 2021 show a downward trend of the glass stream amount in September and October.

Metal stream continuity given by the time section is described through the following chart:

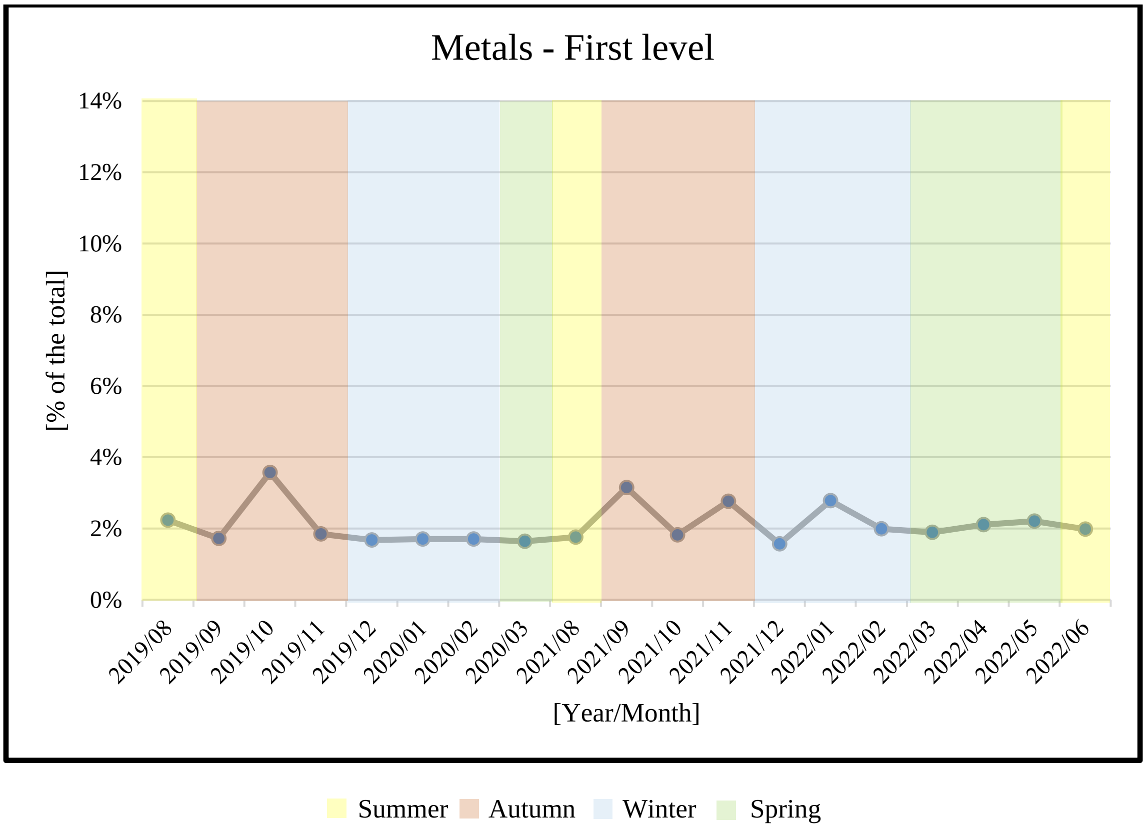

Figure 5-13 Metal stream changes 1. level

Figure 5-13 and Table 5-2 show the amount of metal waste stream in municipal solid waste with a value between 2 and 4%. The maximum mean value of the metal stream was recorded in October 2019 with $\bar{X}_{metal,mean,max}$ = 3.57%. The lowest mean value was recorded in December 2021 with $\bar{X}_{metal,mean,min}$ = 1.57%. The average metal stream mean value through the whole dataset is $\bar{X}_{metal,mean,avrg}$ = 2.11%.

According to Figure 5-13, the metal waste maintains a constant value in the municipal solid waste with small deviations observable in the autumn months.

CONCLUSION FOR THE FIRST LEVEL

The first level in municipal solid waste analysis allows for gaining basic knowledge about the composition of municipal solid waste. With an average amount of 29.91%, biodegradable waste represents the most voluminous stream in municipal solid waste. Values of all waste streams defined by the methodology in the first-level municipal solid waste composition analysis are shown in Figure 5-14. Table 5-3 shows the average, maximum, and minimum values of the following waste streams in the first level. The first level describes which category should be focused on inside the third level of waste composition analysis. The first level does not provide enough specific information about the fractions that make up the waste stream to be able to give recommendations for waste treatment. The third level of the waste composition analysis shall bring a higher understanding of each category.

Category	Average	Max	Min
Paper	6.49%	9.67%	2.89%
Plastic	6.88%	12.25%	3.00%
Bio	29.91%	59.55%	21.77%
Wood - treated	0.67%	1.87%	0.01%
Glass	3.15%	4.82%	1.38%
Metals	2.11%	3.57%	1.57%

Table 5-3 Average, maximum, minimum values of the given streams across the timeline

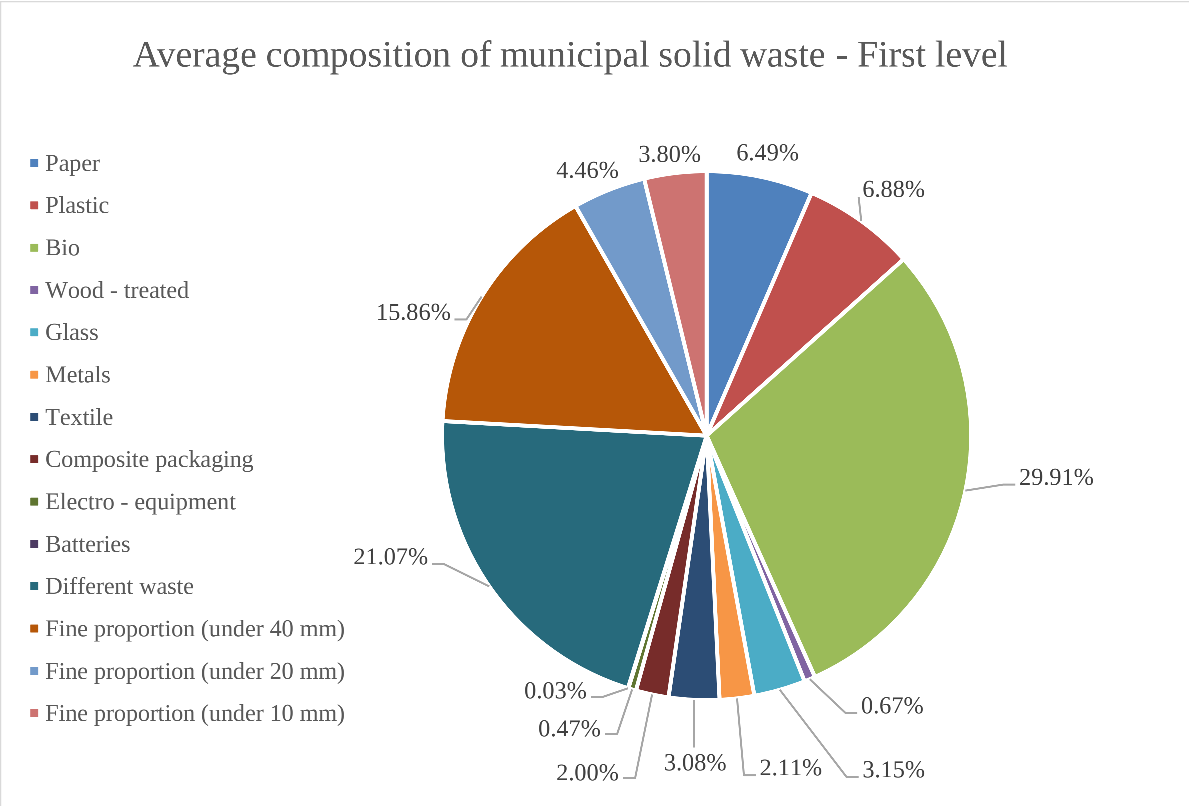

Figure 5-14 Average composition of municipal solid waste 1. level

5.3.2 Municipal solid waste composition analysis in the third level

Municipal solid waste composition analysis in the third level introduces an extension of monitored categories described in Chapter 5.3.1. The third level analyses the waste stream in more detail. The information about the composition of the chosen stream gained in the third level allows to bring possible solutions for the waste treatment of municipal solid waste. The following chapter presents gained knowledge of each category in relation to the timestamp and composition of municipal solid waste. Each category is accompanied by a figure describing the structure of the given waste stream with the defined levels. Levels are distinguished by the following colours:

- Level 1 – Orange
- Level 2 – Blue
- Level 3 – Grey

The waste composition analysis in the third level draws from the same dataset as the first level. The process of data collection was described in the chapter 5.1.

5.3.2.1 PAPER WASTE STREAM – THIRD LEVEL

According to the waste composition analysis in the first level, the municipal solid waste contains 6.5% of the paper waste stream. The waste composition in the third level categorizes the paper stream into groups described in Figure 5-15:

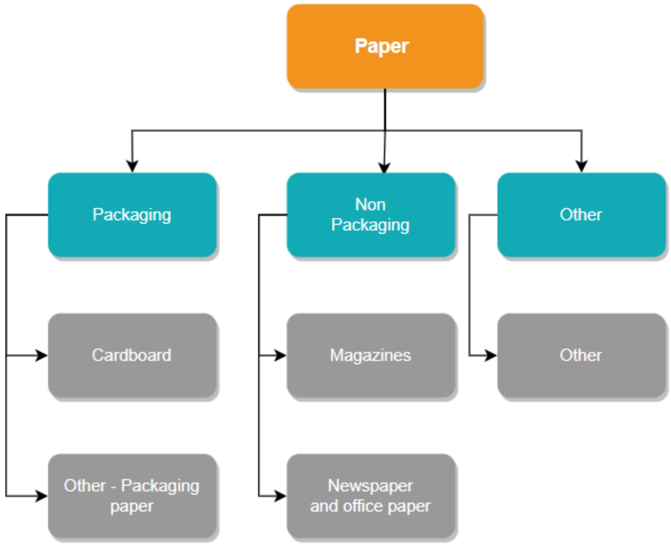

Figure 5-15 Paper stream structure

The changes in the percentage of the given paper category in the third level of municipal solid waste analysis are assessed over the timeline of the dataset collection. The changes are shown in the following charts:

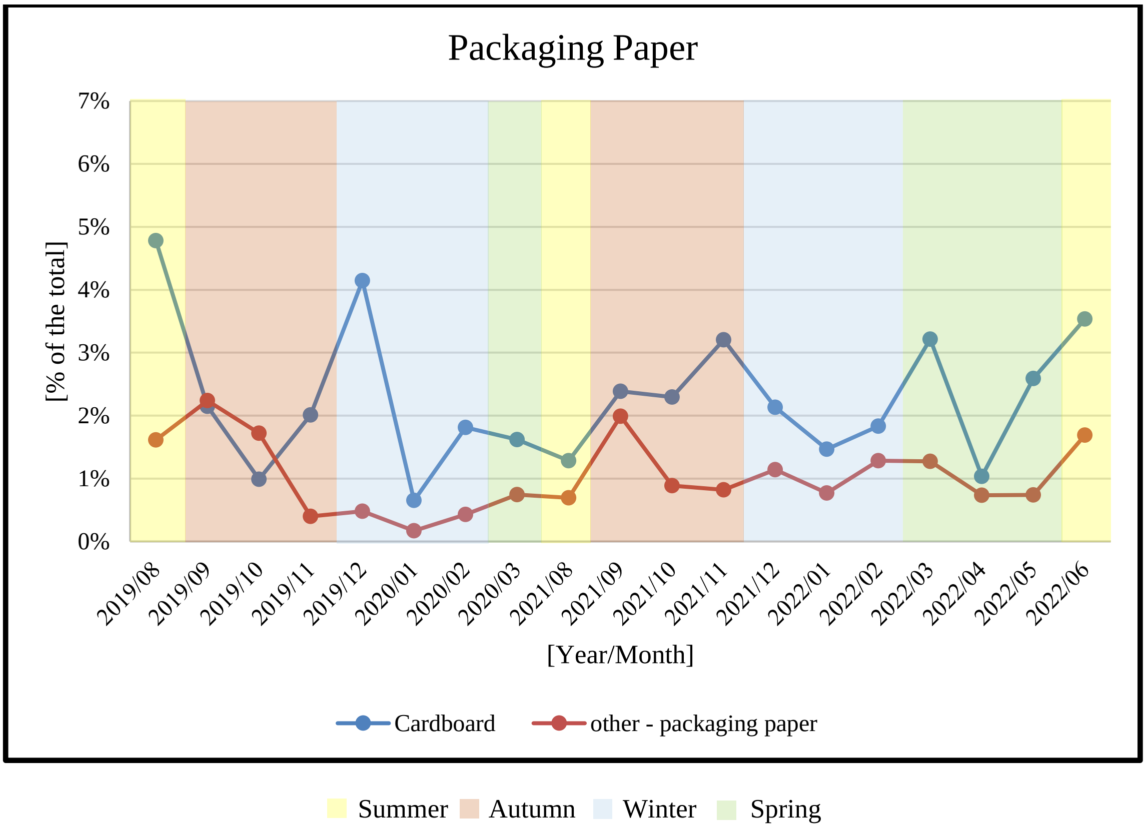

Figure 5-16 Packaging paper fractions

According to Figure 5-16, packaging paper is the most significant category, which creates almost half of the total amount of paper waste stream. The Cardboard is the largest category of the paper family with the average mean value $\bar{X}_{Cardboard,mean,avrg}$ = 2.27%. The other packaging paper holds the average mean value $\bar{X}_{Other-packaging,mean,avrg}$ = 1.07%. The chart reports an increase in the packaging paper over the following time. The growth of packaging paper in municipal waste can be attributed to the popularity of e-commerce and online shopping. As an interesting trend that can be pointed out is the decrease in packaging paper in January 2020 and 2022. The winter holiday season could be seen as a possible prerequisite for an increase in the value of packaging. The opposite results provided by the municipal solid waste composition analysis can be explained by the high recycling activity in the society in the Czech Republic.

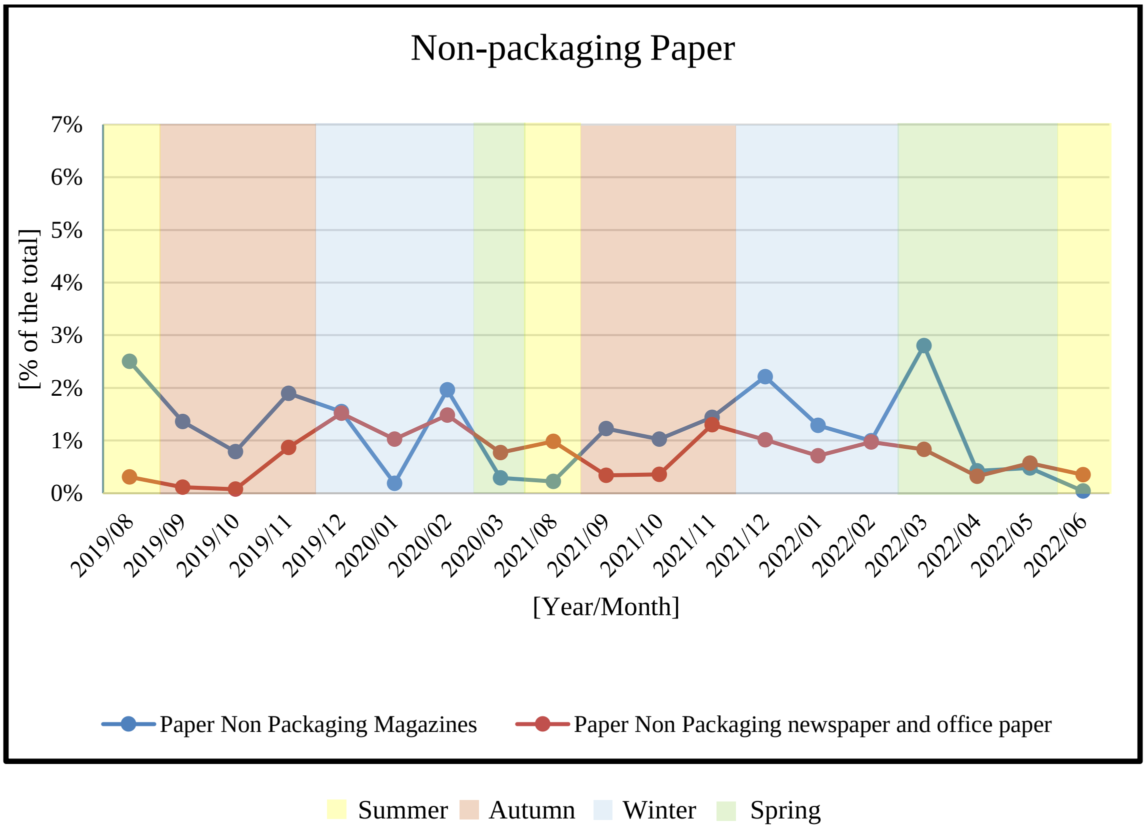

Figure 5-17 Non packaging paper fractions

As Table 5-4 shows, the non-packaging paper represents around 30% of the total paper waste stream in municipal solid waste. The magazine's average mean value is $\bar{X}_{Magazines,mean,avrg}$ = 1.20%. Figure 5-16 shows the instability of the magazine waste stream, with the maximum mean value of $\bar{X}_{Magazines,mean,max}$ = 2.80% recorded in March 2022 and the lowest mean value recorded in June 2022 with $\bar{X}_{magazines,mean,min}$ = 0.04%. The newspaper and office paper average mean value is $\bar{X}_{news/office,mean,avrg}$ = 0.73%. Figure 5-16 displays the annual trend of newspaper and office paper waste stream decrease in its value with the lowest values recorded during September and October. Lowest mean value $\bar{X}_{news/office,mean,min}$ = 0.08% occurs in September 2019.

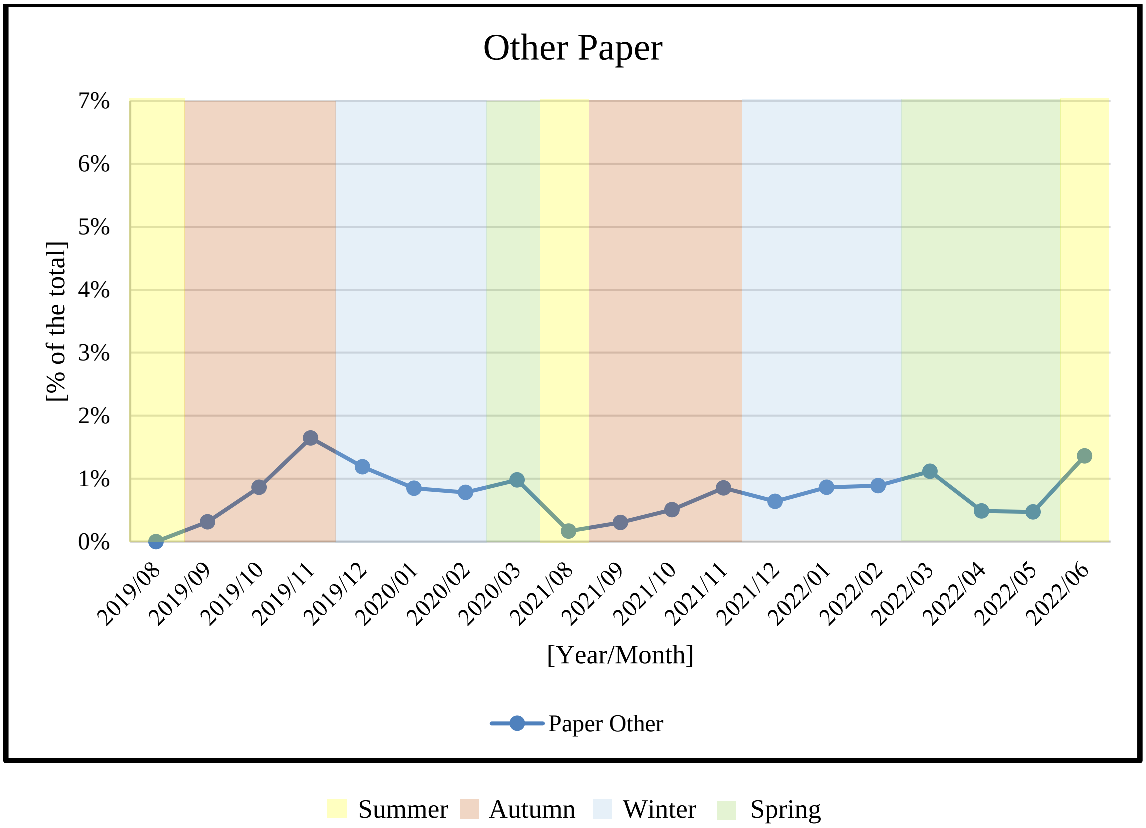

Figure 5-18 Other paper fraction

The other paper category represents the remaining 13% of the total paper waste stream. The other paper's average mean value is $\bar{X}_{Other-paper,mean,avrg}$ = 0.75%. According to Figure 5-18 the lowest values were reported during Augusts, whereas at the start of the experiment in August 2019 none of the other paper categories was registered during the waste screening.

Table 5-4 describes the fractions in the paper waste stream by expressing their maximum, minimum and average values throughout the given experiment. Figure 5-19 shows the average composition of the paper waste stream by fractions studied in the third level.

Level 1	Paper	Paper	Paper	Paper	Paper
Level 2	Packaging	Packaging	Non Packaging	Non Packaging	Other
Level 3	Cardboard	other - packaging paper	Magazines	newspaper and office paper	other paper 3 category
Average	2.27%	1.04%	1.20%	0.73%	0.75%
Max	4.78%	2.24%	2.80%	1.52%	1.65%
Min	0.65%	0.17%	0.04%	0.08%	0.00%
% of the paper	**37.89%**	17.41%	19.96%	12.23%	12.52%

Table 5-4 Specific values of the paper fractions

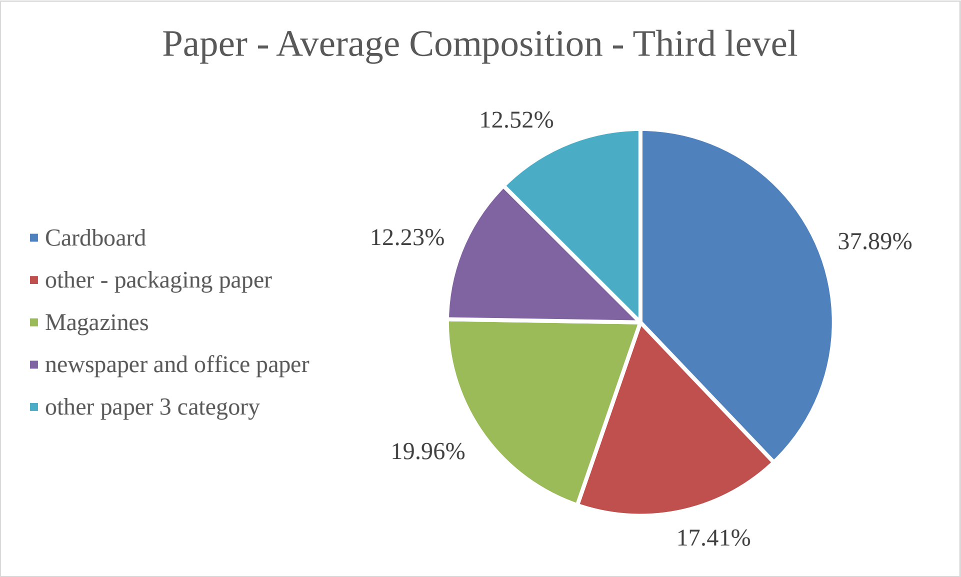

Figure 5-19 Paper - Average Composition

5.3.2.2 PLASTIC WASTE STREAM – THIRD LEVEL

According to the waste composition analysis in the first level, the municipal solid waste contains around 6.9% of the plastic waste stream. The waste composition in the third level categorizes the plastic waste stream into groups described in Figure 5-20:

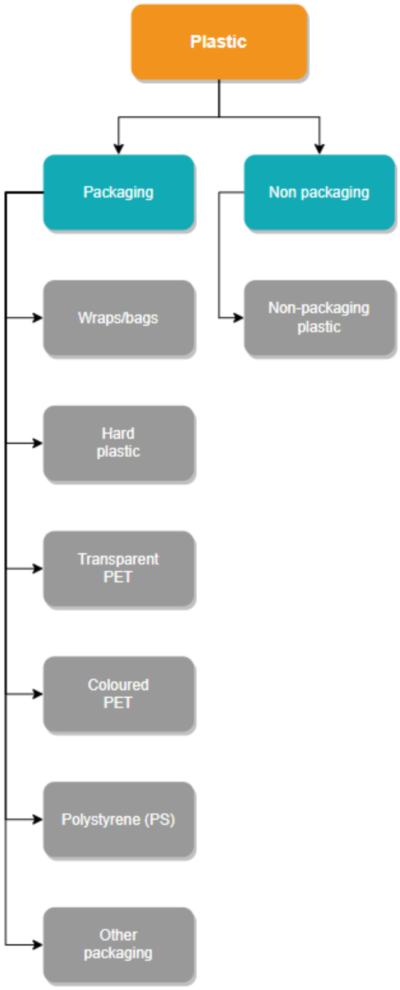

Figure 5-20 Plastic stream structure

The changes in the percentage of the given plastic category in the third level of municipal solid waste analysis are assessed over the timeline of the dataset collection. The changes are shown in the following charts:

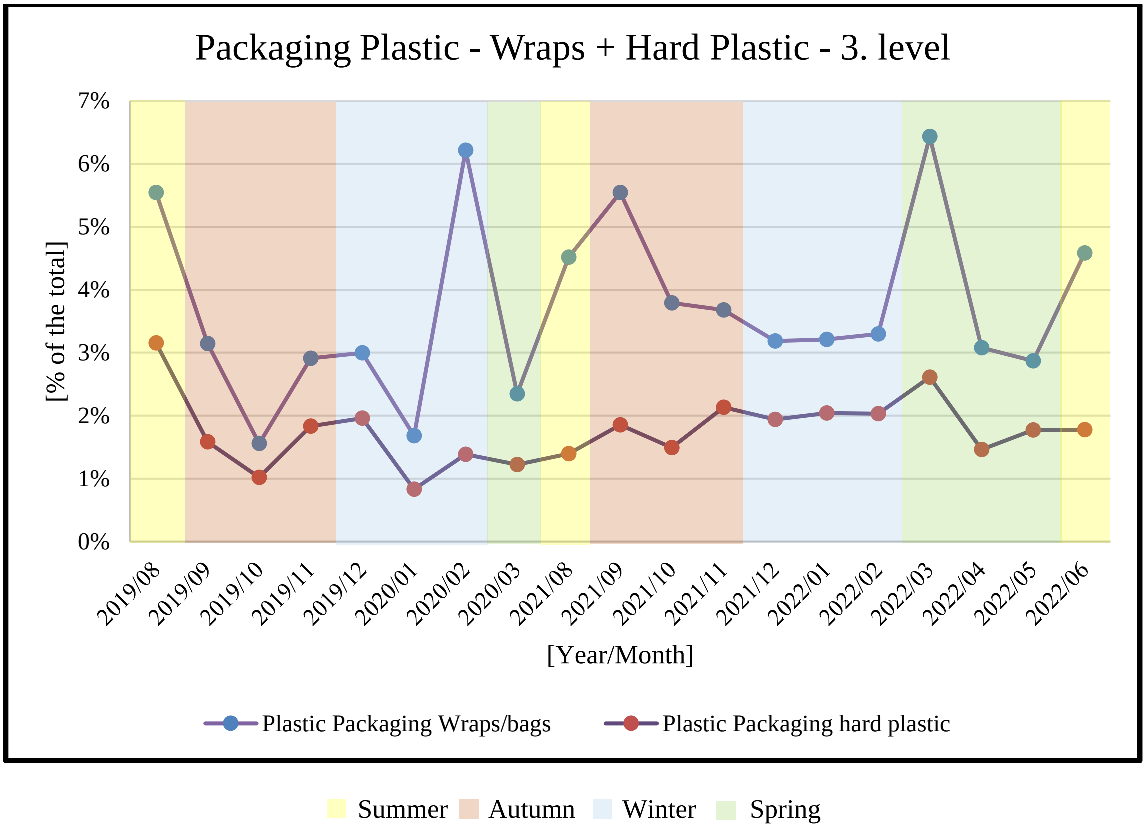

Figure 5-21 Changes in Wraps/bags + Hard Plastic fraction

According to Figure 5-21 and Table 5-5, half of the plastic family is formed by the Wraps/bags category with the average mean value in the municipal solid waste of $\bar{X}_{Wraps,mean,avrg}$ = 3.71%. Figure 5-21 shows the increasing trend during the given time in the plastic wraps amount and the instability of the plastic wraps waste stream with the maximum mean value of $\bar{X}_{Wraps,mean,max}$ = 6.43% recorded in March 2022 and the lowest mean value recorded in October 2019 with $\bar{X}_{Wraps,mean,min}$ = 1.56%. Hard plastic creates around a quarter of the plastic in municipal solid waste with the average mean value of $\bar{X}_{Hard-plastic,mean,avrg}$ = 1.76%. Figure 5-21 shows the increasing trend from January 2020, where the minimum mean value is recorded with $\bar{X}_{Hard-plastic,mean,min}$ = 0.83%. The amount of hard plastic in municipal solid waste stays above 1% for the remainder of the measurement.

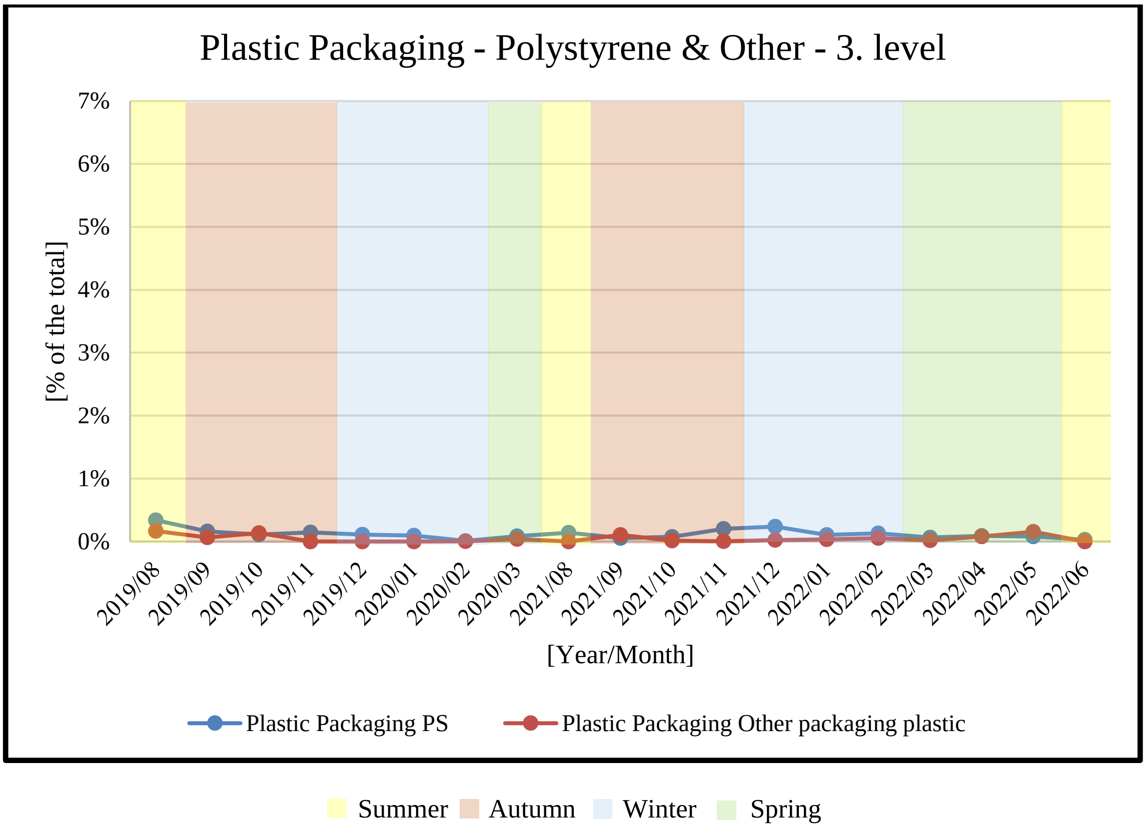

Figure 5-22 Changes in Polystyrene + Other packaging plastic fraction

According to Figure 5-22 and Table 5-5, Polystyrene and Other plastic packaging represent the smallest categories in the plastic family with the average mean values of $\bar{X}_{Polystyrene,mean,avrg}$ = 0.12% and $\bar{X}_{Other-packaging-plastic,mean,avrg}$ = 0.05%. Polystyrene's use in the public sector comes in the way of food containers. Polystyrene's low amount of municipal solid waste can be connected to the Europe Directive on single-use plastics. The Directive aims to reduce the amount of single-use plastic items together with the promotion of sustainable alternatives. The low amount of other packaging plastic throughout the given experiment can be explained by the high categorization of packaging plastic in the third level of municipal waste analysis.

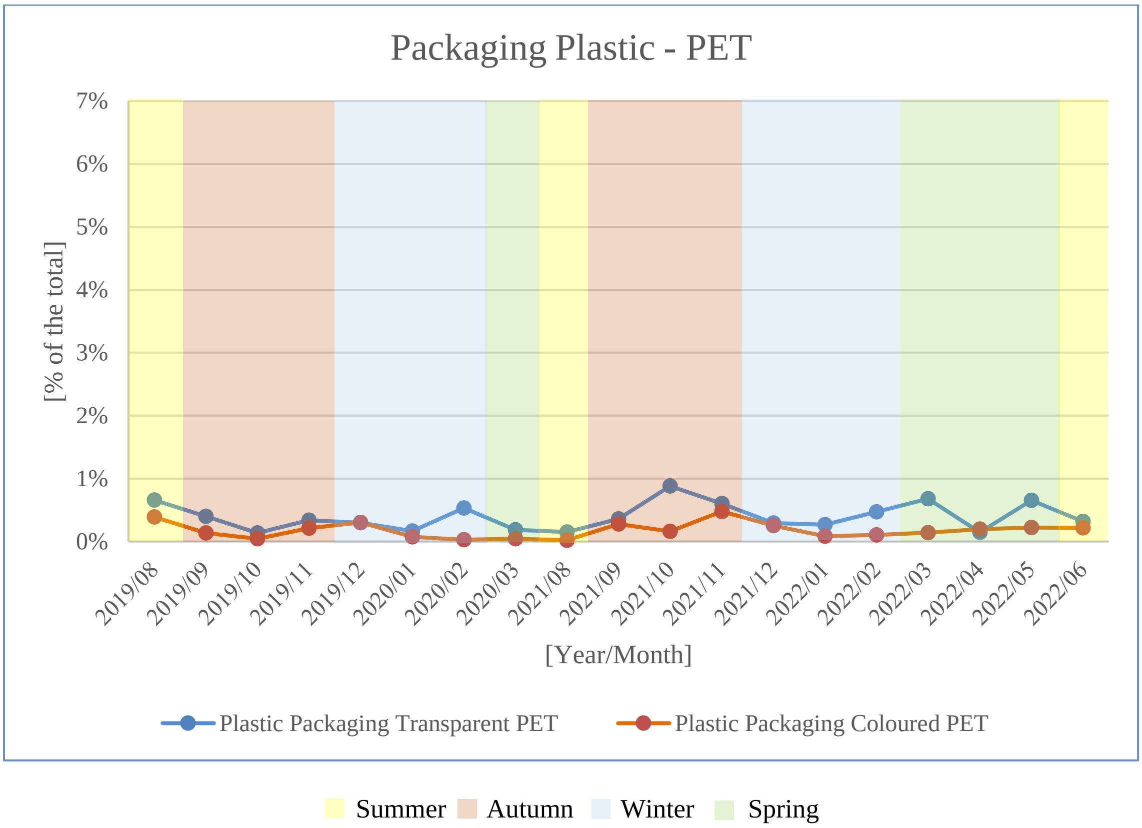

Figure 5-23 Changes in PET fractions

Based on Figure 5-23 and Table 5-5, the Plastic PET category represents around 9% of the plastic waste stream. The average mean values of transparent and coloured PET in the municipal solid waste respectively are $\bar{X}_{Transparent-PET,mean,avrg}$ = 0.40% and $\bar{X}_{Coloured-PET,mean,avrg}$ = 0.18%. According to Figure 5-23, during the monitored time, the average mean value for transparent PET does not across the value of 1% in municipal solid waste with the maximum value of $\bar{X}_{Transparent-PET,mean,max}$ = 0.88% from October 2021. The coloured PET peak mean value is $\bar{X}_{Coloured-PET,mean,max}$ = 0.04% from November 2021. The low amount of PET contained in municipal solid waste reflects the high recycling activity of plastic materials in the Czech Republic.

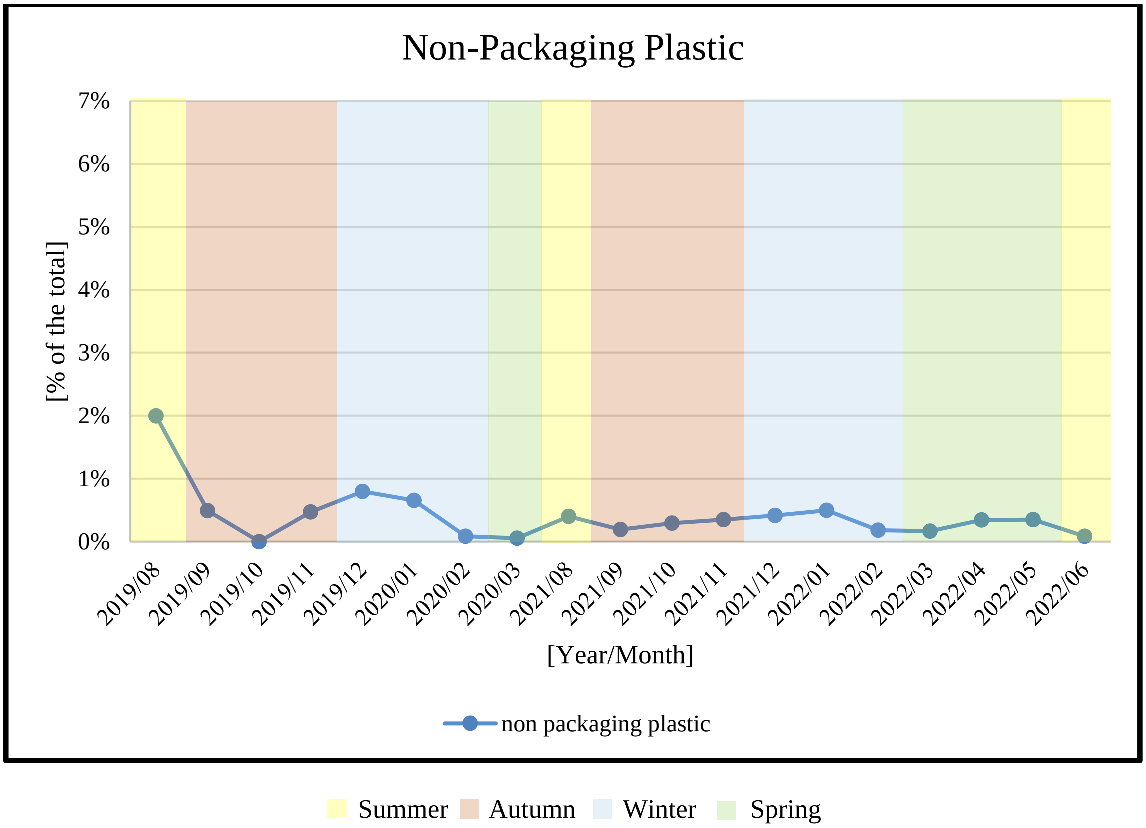

Figure 5-24 Changes in non-packaging plastic fraction

As Figure 5-24 and Table 5-5 show, the non-packaging plastic category represents the remaining 6.2% of the total plastic waste stream. The non-packaging plastic average mean value is $\bar{X}_{Non-packaging-plastic,mean,avrg}$ = 0.41%. According to Figure 5-24 the non-packaging plastic does not exceed the value of 1% in the municipal solid waste during the whole experiment except for the maximum mean value of $\bar{X}_{Non-packaging-plastic,mean,max}$ = 1.99%, collected in August 2019. The visible trend from the chart is the gradual decrease over the studied time of the non-packaging plastic category in municipal solid waste. As an example of non-packaging plastic can be mentioned single-use plastics – cutlery, coasters etc.

Table 5-5 describes the fractions in the plastic waste stream by expressing their maximum, minimum and average values throughout the given experiment. Figure 5-25 the average composition of the plastic waste stream by fractions studied in the third level.

Level 1	Plastic	Plastic	Plastic	Plastic	Plastic	Plastic	Plastic
Level 2	Packaging	Packaging	Packaging	Packaging	Packaging	Packaging	Non Packaging
Level 3	Wraps/bags	hard plastic	Transparent PET	Coloured PET	PS	Other packaging plastic	non-packaging plastic
Average	3.71%	1.76%	0.40%	0.18%	0.12%	0.05%	0.41%
Max	6.43%	3.15%	0.88%	0.48%	0.34%	0.17%	1.99%
Min	1.56%	0.83%	0.14%	0.02%	0.01%	0.00%	0.00%
% in the stream	56.05%	26.60%	5.97%	2.68%	1.78%	0.71%	6.20%

Table 5-5 Specific values of the plastic fractions

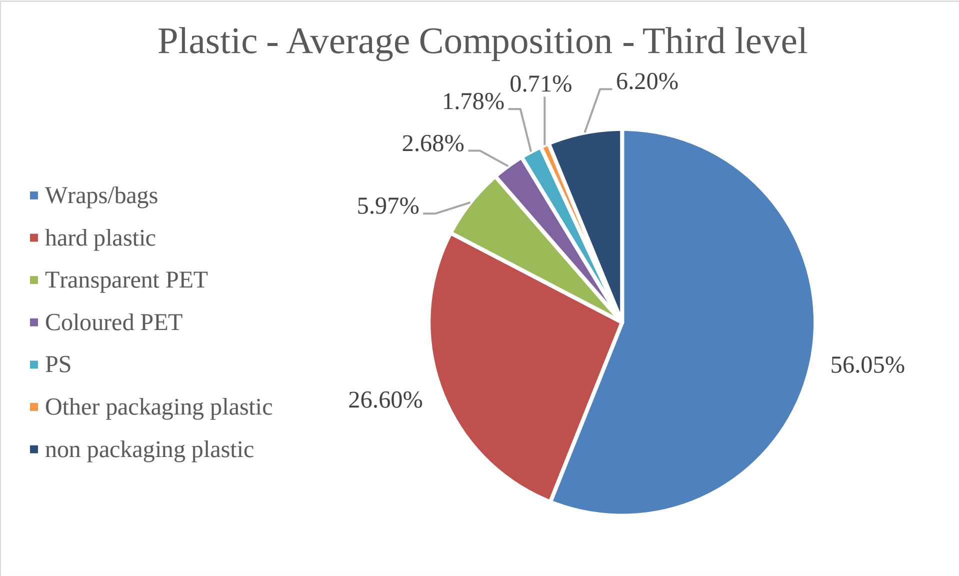

Figure 5-25 Plastic stream - average composition

5.3.2.3 Biodegradable waste stream – third level

According to the waste composition analysis in the first level, the municipal solid waste contains almost 30% of the biodegradable waste stream. The waste composition in the third level categorizes the biodegradable waste stream into groups described in Figure 5-26:

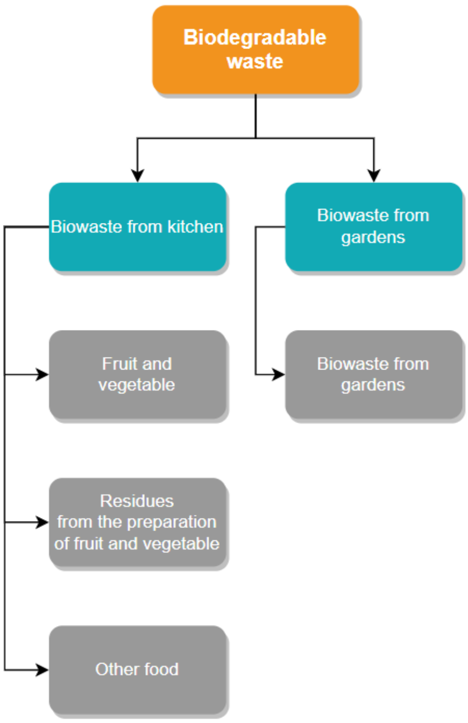

Figure 5-26 Biodegradable waste stream structure

The changes in the percentage of the given biodegradable waste category in the third level of municipal solid waste analysis are assessed over the timeline of the dataset collection. The changes are shown in the following charts:

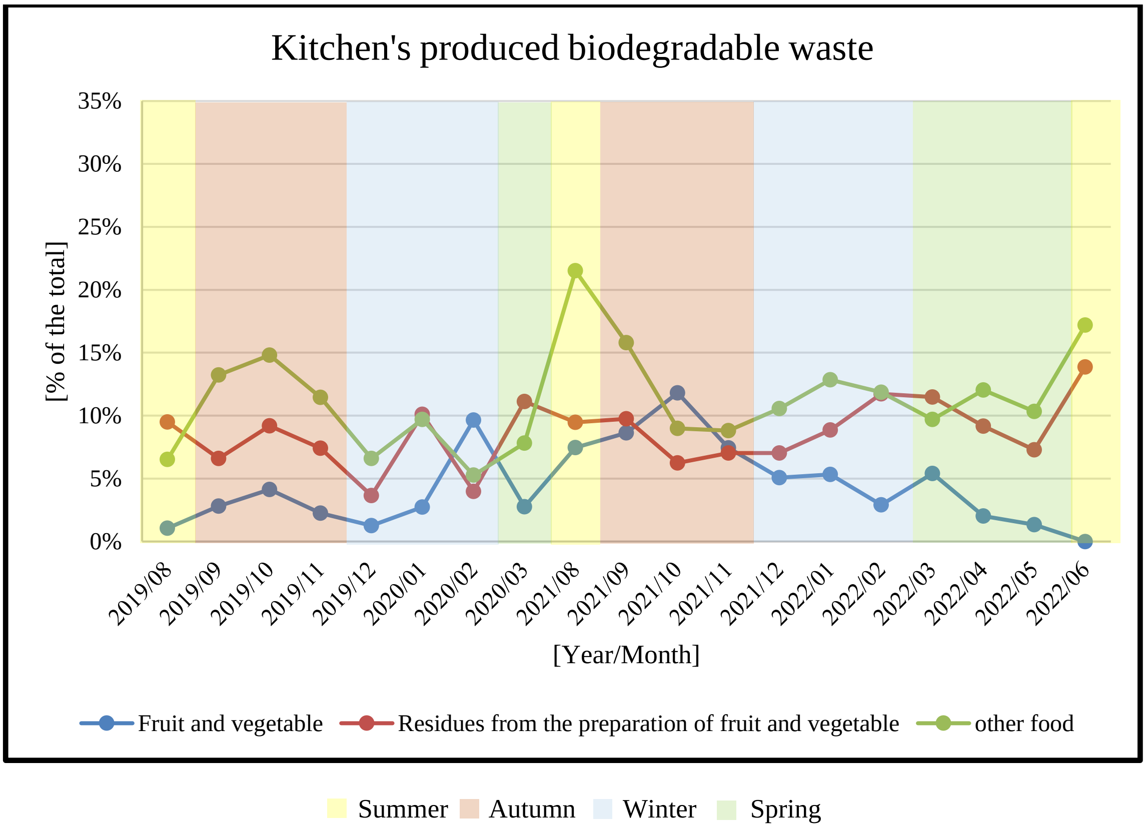

Figure 5-27 Changes in kitchen's produced fractions

According to Figure 5-27 and Table 5-6, the kitchen's produced biodegradable waste represents around 80% of the total biodegradable waste stream. The other food category holds the highest average mean value from the biodegradable waste family with a value of $\bar{X}_{Other-food,mean,avrg}$ = 11.32%. The average mean values for the fruit and vegetable and the residues from the preparation of the fruit and vegetable are $\bar{X}_{Fruit\&Vegetable,mean,avrg}$ = 4.42%, $\bar{X}_{Residues,mean,avrg}$ = 8.60%. Figure 5-27 highlights the stability of the other food's waste stream during the monitored time. The chart shows the close connection between the categories of fruit and vegetable and their residues created by the preparation process. The rise in value in one category does come with a downfall in the value of the other one.

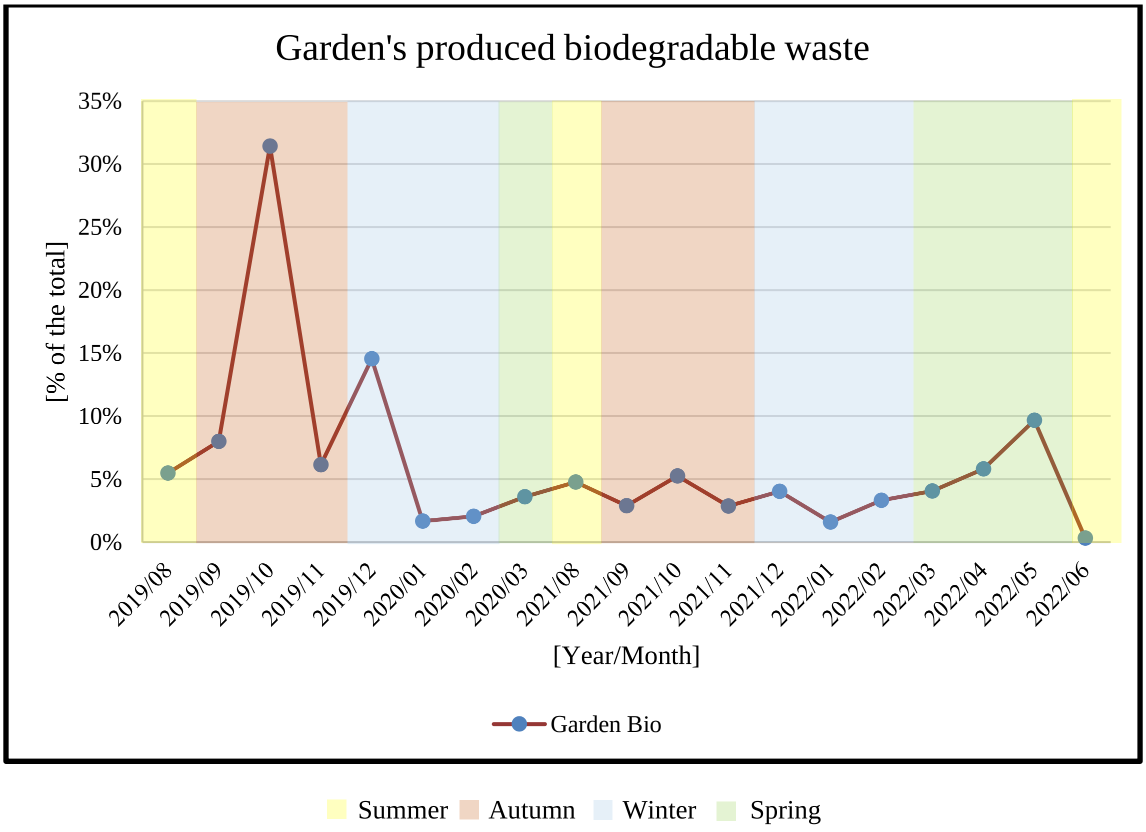

Figure 5-28 Changes in garden biowaste fraction

As Figure 5-28 and Table 5-6 show, the biodegradable waste produced from gardens represents around 20% of the total biodegradable waste stream. The garden's produced biodegradable waste average mean value is $\bar{X}_{Garden-Bio,mean,avrg}$ = 6.18%. According to Figure 5-28 the non-packaging plastic does not exceed the value of 1% in the municipal solid waste during the whole experiment except for the maximum mean value of $\bar{X}_{Non-packaging-plastic,mean,max}$ = 1.99%, collected in August 2019. The visible trend from the chart is the gradual decrease over the studied time of the non-packaging plastic category in municipal solid waste.

The waste composition analysis shows that the biodegradable waste can be considered as a stable waste stream. The way of collection of biodegradable waste is not unified in the Czech Republic. The peaks and lows in certain categories can be explained by the mentioned diversification of the waste collection process. Village households report different tactics for biowaste treatment compared to city households. Villages households are expected to use the biowaste for composting compared to the city households where the biodegradable waste is mainly part of the municipal solid waste.

Table 5-6 describes the fractions in the biodegradable waste stream by expressing their maximum, minimum and average values throughout the given experiment. Figure 5-29 shows the average composition of the biodegradable waste stream by fractions studied in the third level.

Level 1	Bio	Bio	Bio	Bio
Level 2	Kitchen based	Kitchen based	Kitchen based	Garden-based
Level 3	Fruit and vegetable	Residues from the preparation of fruit and vegetable	other food	Garden Bio
Average	4.42%	8.60%	11.32%	6.18%
Max	11.81%	13.87%	21.51%	31.43%
Min	0.00%	3.65%	5.27%	0.32%
% in the stream	14.49%	28.18%	37.07%	20.25%

Table 5-6 Specific values of the biodegradable waste fractions

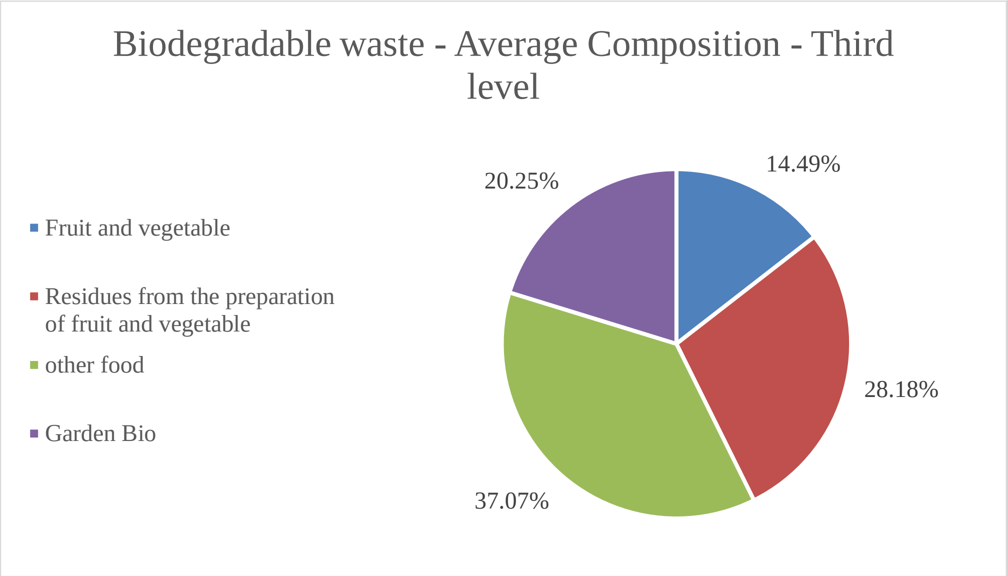

Figure 5-29 Biodegradable waste stream average composition

5.3.2.4 GLASS WASTE STREAM – THIRD LEVEL

According to the waste composition analysis in the first level, the municipal solid waste contains around 3% of the glass waste stream. The waste composition in the third level categorizes the glass waste stream into groups described in Figure 5-30:

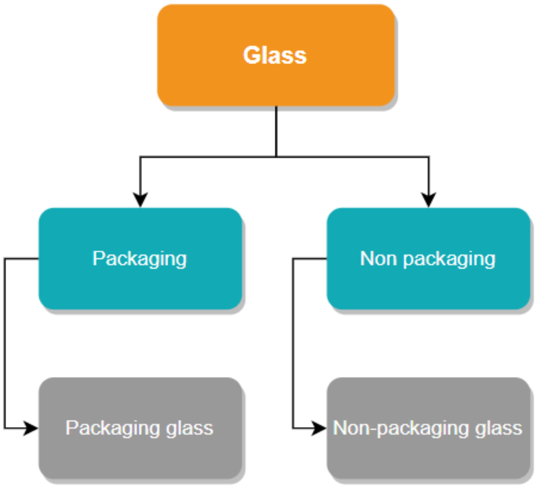

Figure 5-30 Glass stream structure

The changes in the percentage of the given glass waste stream in the third level of municipal solid waste analysis are assessed over the timeline of the dataset collection. The changes are shown in the following charts:

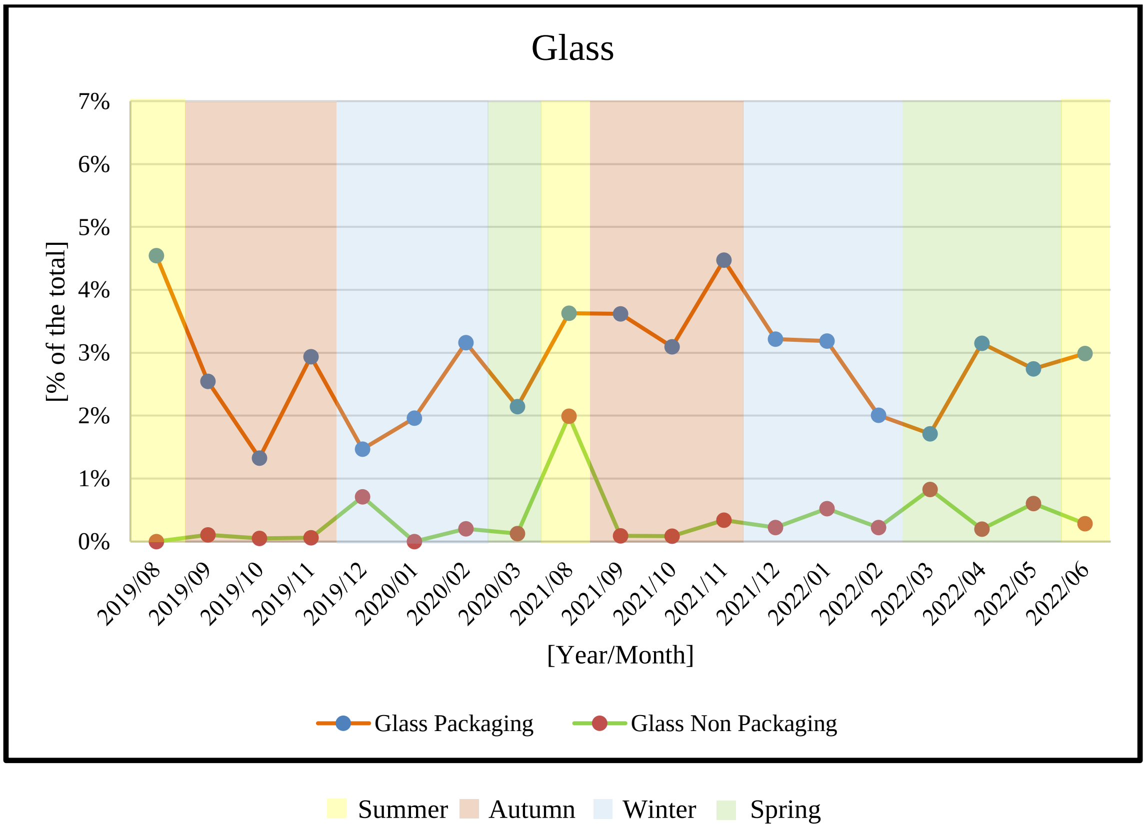

Figure 5-31 Changes in glass packaging and non packaging fractions

The glass waste stream is distinguished into packaging and non-packaging glass. According to Figure 5-31 and Table 5-7, the average mean amount of packaging glass in municipal solid waste is $\bar{X}_{Glass-packaging,mean,avrg}$ = 2.84% and the value of non-packaging glass is

$\bar{X}_{Glass-Non-packaging,mean,avrg}$ = 0.35%. Figure 5-31 highlights a rising trend in the mean value of the non-packaging glass expressed by the year 2022.

Overall, the data show a small amount of the glass category in the municipal solid waste. The values for glass categories are tolerable. Reduction of value in a particular category is possible by raising the consumer's motivation for recycling or by reduction of production in the chosen category.

Table 5-7 describes the fractions in the glass waste stream by expressing their maximum, minimum and average mean values throughout the given experiment. Figure 5-32 shows the average composition of the glass waste stream by fractions studied in the third level.

Level 1	Glass	Glass
Level 2	Packaging	Non Packaging
Level 3	Packaging Glass 3 level	Non packaging glass 3 level
Average	2.84%	0.35%
Max	4.55%	1.99%
Min	1.33%	0.00%
% in the stream	89.01%	10.99%

Table 5-7 Specific values of the glass fractions

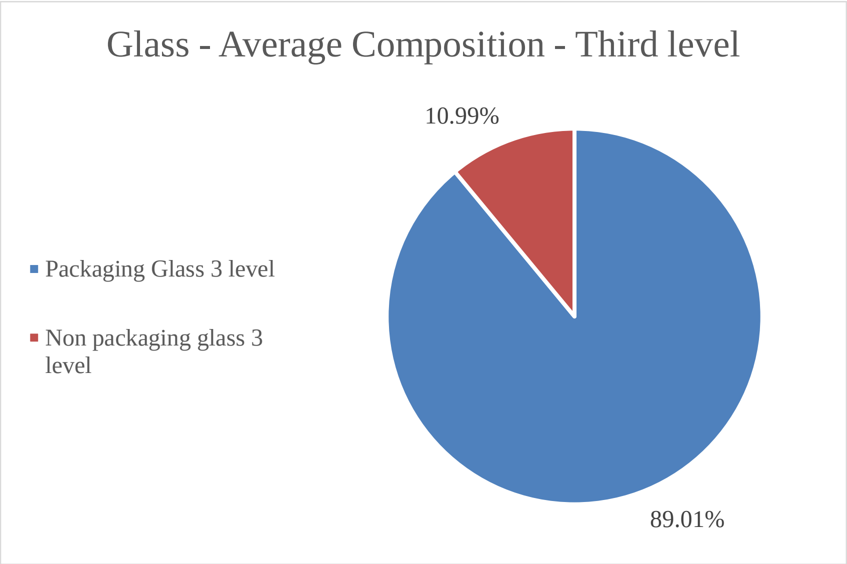

Figure 5-32 Glass stream average composition

5.3.2.5 METAL WASTE STREAM – THIRD LEVEL

According to the waste composition analysis in the first level, the municipal solid waste contains around 2% of the metal waste stream. The waste composition in the third level categorizes the biodegradable waste stream into groups described in Figure 5-33:

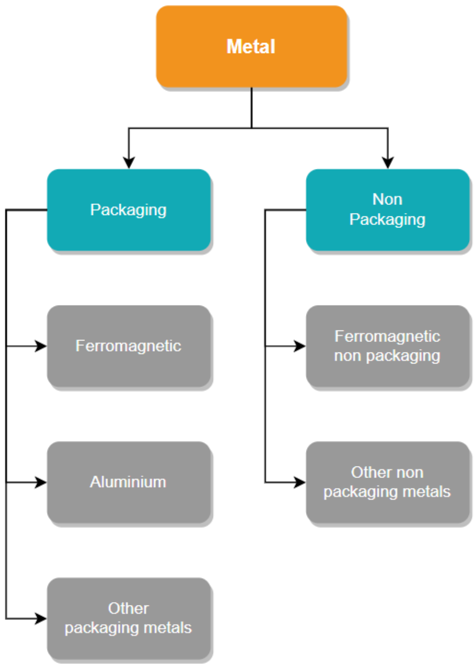

Figure 5-33 Metal stream structure

The changes in the percentage of the given metal waste category in the third level of municipal solid waste analysis are assessed over the timeline of the dataset collection. The changes are shown in the following charts:

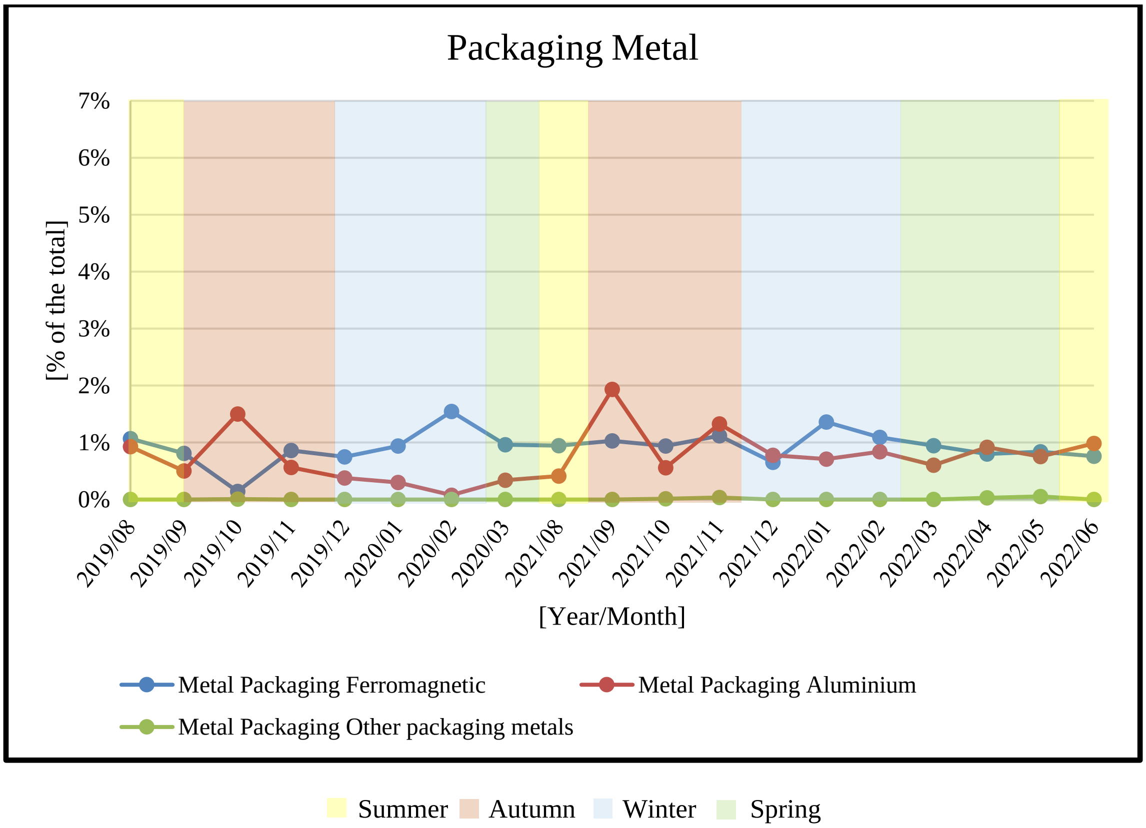

Figure 5-34 Changes in fractions of packaging metal

According to Figure 5-34 and Table 5-8, packaging metal creates around 80% of total metal waste in municipal solid waste, with an average mean value in municipal solid waste during the experiment for the ferromagnetic packaging category $\bar{X}_{Packaging-Ferromagnetic,mean,avrg}$ = 0.92% and for the Aluminium packaging category $\bar{X}_{Packaging-Aluminium,mean,avrg}$ = 0.76%. Figure 5-34 shows the stability of the ferromagnetic packaging category with small peaks during the measurements and the rise in the mean value of the aluminium packaging category when the values from November 2019 to March 2020 and November 2021 to March 2022 are compared. The other packaging metals were included in the municipal solid waste with a small or zero value during the measurements.

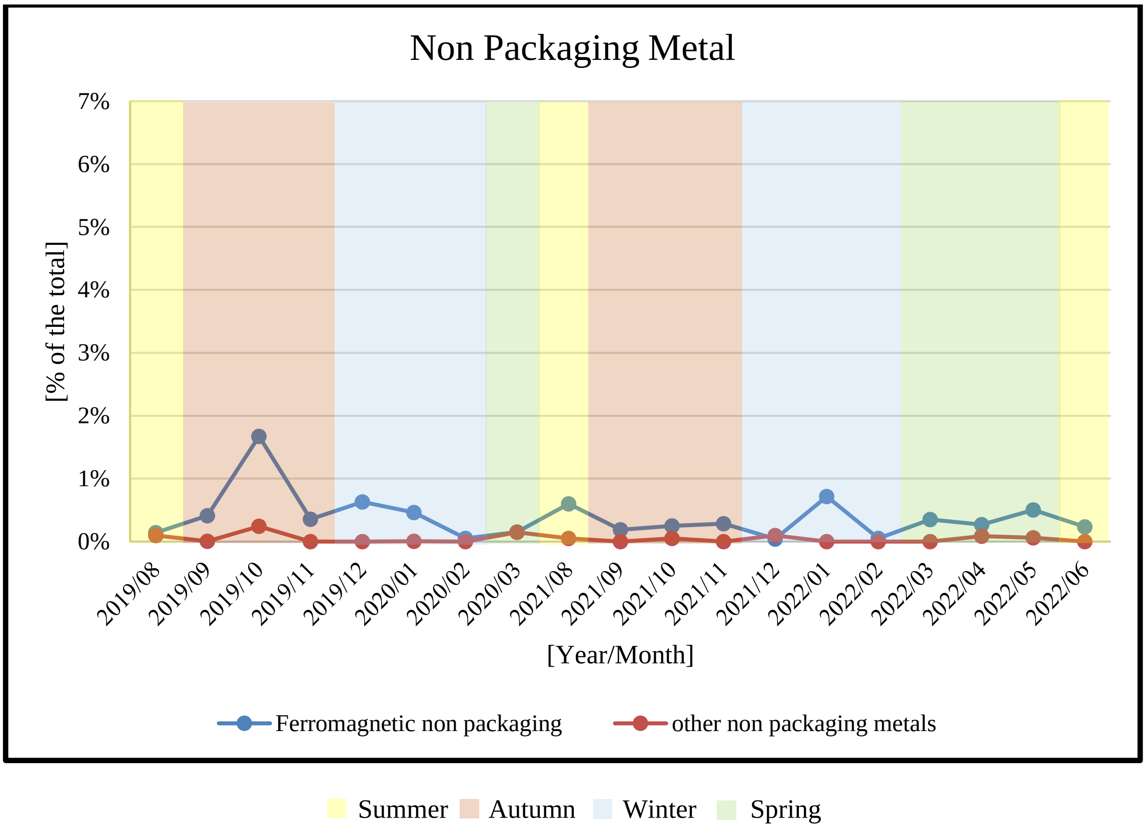

Figure 5-35 Changes in fractions of non packaging metal

Figure 5-35 and Table 5-8 show low mean values during the experiment of non-packaging metals, where the ferromagnetic non-packaging category average mean value in the municipal solid waste is $\bar{X}_{Non-packaging-Ferromagnetic,mean,avrg}$ = 0.39%. According to Figure 5-35, the mean value of the ferromagnetic non-packaging category does not exceed 1% in the municipal solid waste except for October 2019 and the peak value of $\bar{X}_{Non-packaging-Ferromagnetic,mean,max}$ = 1.67%. The other non-packaging metals were included in the municipal solid waste with a small or zero value during the measurements.

Overall, the metal waste stream occupies a small space in municipal solid waste. The waste composition analysis does not show a visible potential for a rise in value in researched categories.

Table 5-8 describes the fractions in the metal waste stream by expressing their maximum, minimum and average values throughout the given experiment. Figure 5-36 shows the average composition of the metal waste stream by fractions studied in the third level.

Level 1	Metal	Metal	Metal	Metal	Metal
Level 2	Packaging	Packaging	Packaging	Non Packaging	Non Packaging
Level 3	Ferromagnetic	Aluminium	Other packaging metals	Ferromagnetic non packaging	other non-packaging metals
Average	0.92%	0.76%	0.01%	0.39%	0.04%
Max	1.54%	1.93%	0.05%	1.67%	0.24%
Min	0.14%	0.08%	0.00%	0.04%	0.00%
% in the stream	43.55%	35.73%	0.36%	18.28%	2.08%

Table 5-8 Specific values of the metal fractions

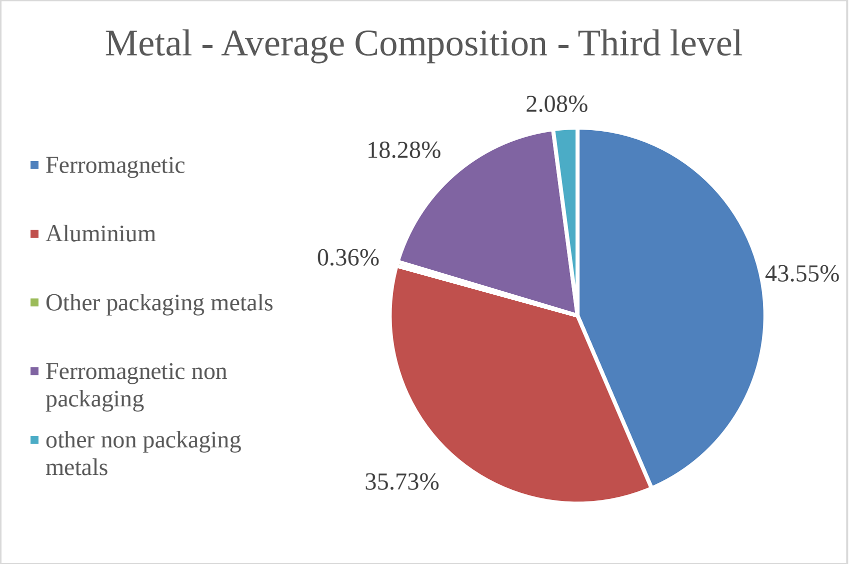

Figure 5-36 Metal stream average composition

5.3.3 LOCATION-BASED CHANGES IN THE FIRST LEVEL

As was presented in the theoretical part of the master thesis, area of the waste generation is one of the key factors for the municipal solid waste composition. Examination of the waste composition of different locations can bring valuable knowledge and insight into the challenges of waste management in given regions or locations with similar features. The locations selected for this research are based on the guidelines and requirements outlined by the Czech methodology TIRSMZP719. To ensure that the research findings are reliable and representative of waste composition in different regions, a diverse range of municipalities from across the Czech Republic was chosen with the use of clustering. Clustering is the process of grouping data, or in this example, places, according to their shared properties. The groups formed through clustering are called clusters. Adherence to established guidelines for location selection ensures the accuracy and applicability of the research results.

The thesis will present the results of the waste composition analysis of representatives from 9 different clusters. For each cluster will be shown only categories with material or energy reuse potential – Paper, Plastic, and Biodegradable waste. The presented results are calculated in the first level of waste composition analysis of the TIRSMZP719 methodology. The analysis follows the same procedure as was presented for the analysis in Chapter 5.3.1.

- First cluster

The first cluster can be described by the following characteristic patterns:

- Population: Over 100 000 inhabitants
- Housing Area: Dense
- Regional centres

For the first researched cluster Table 5-9 and Figure 5-37 show, the biodegradable waste stream represents on average around 24% of the total municipal solid waste generated in this area, which makes the biodegradable waste the biggest waste stream of municipal solid waste. Across the observed timeline, the biodegradable waste raises its value with the maximum value of 33.26% recorded in August 2021. The plastic category shows a declining trend in value over time. The trend can be caused by a good and effective waste management plan of the given municipality. The paper category oscillates around the value of 10% over the examined time.

Date	Paper	Plastic	Bio
2019/08	9.22%	12.25%	22.55%
2019/09	13.30%	10.72%	16.24%
2019/11	8.99%	7.59%	25.00%
2019/12	14.86%	10.57%	15.11%
2020/02	7.20%	9.38%	22.03%
2020/03	7.85%	5.33%	20.59%
2021/08	10.46%	8.82%	33.26%
2021/11	8.67%	8.66%	23.66%
2022/03	9.76%	5.34%	30.05%

Table 5-9 Database - 1. cluster

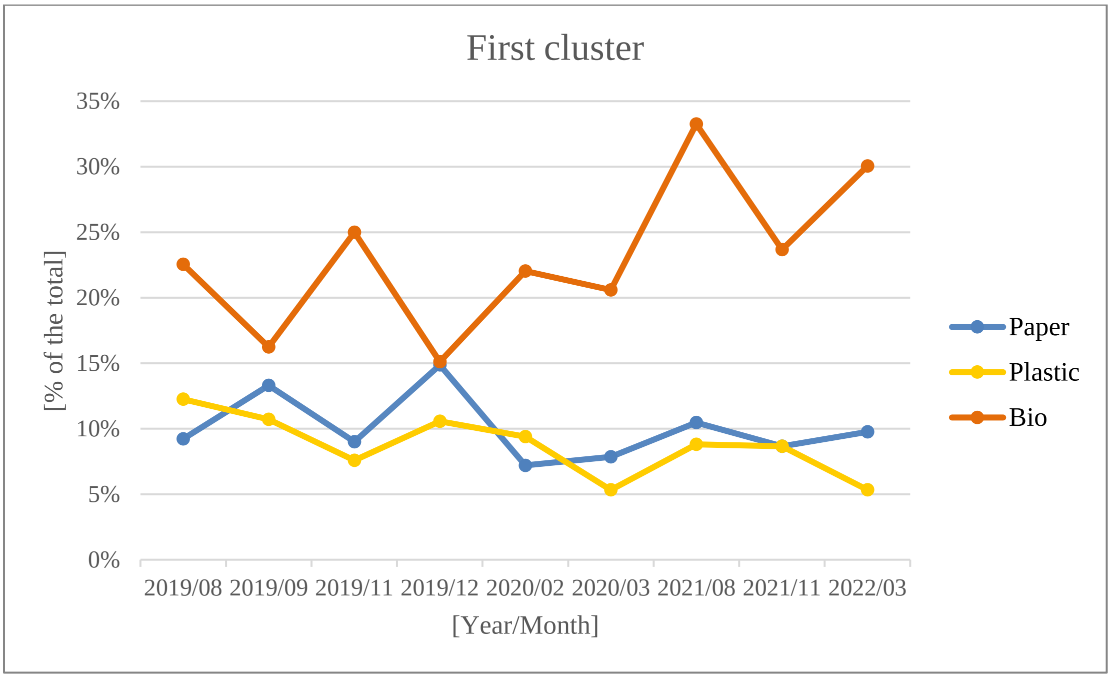

Figure 5-37 Changes in paper, plastic, biodegradable waste streams - 1. cluster

- Second cluster

The second presented cluster is specified by the following characteristic patterns:

- Population: Units of ten thousand inhabitants
- Local district centres

In the second researched cluster Table 5-10 and Figure 5-38 show results with greater instability of watched waste streams in comparison to the first cluster. The results in March 2022 show the plastic stream maximum value of around 27% and the paper stream maximum value of around 16%. These values also stand out in comparison to the overall results in the first level of the paper and plastic stream. Across the following timeline, plastic and paper streams do not drop under the value of 5%. The biodegradable waste stream shows, as in the first cluster, a rising trend in value and is the biggest stream in this municipality. The difference in results in comparison to the general results shows the importance of the right choices in the preparation process of the waste composition analysis.

Date	Paper	Plastic	Bio
2020/02	6.21%	8.48%	20.78%
2021/10	6.25%	6.73%	27.43%
2021/11	12.67%	6.54%	14.25%
2021/12	11.24%	10.46%	17.87%
2022/01	5.96%	5.03%	26.41%
2022/02	6.53%	7.14%	29.47%
2022/03	16.47%	27.22%	19.18%
2022/04	4.70%	8.38%	31.30%
2022/05	5.81%	7.22%	37.75%

Table 5-10 Database - 2. cluster

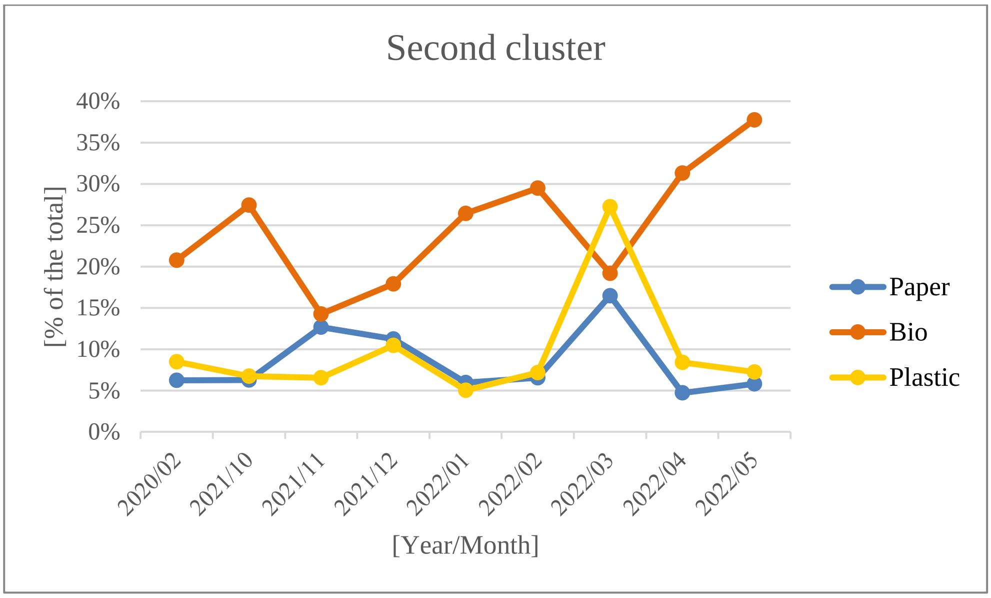

Figure 5-38 Changes in paper, plastic, biodegradable waste streams - 2. cluster

- Third cluster

The third presented cluster is specified by the following characteristic patterns:

- Cities with more village pattern
- Close to the cities defined by the first cluster

In the third cluster Table 5-11 and Figure 5-39 show results with a high potential for reuse of the biodegradable waste stream. Municipalities with a village type of household shall have a higher predisposition for the generation of biodegradable waste. Paper stream declares low values of around 5% in municipal solid waste during the following time in comparison to the general research. Plastic stream value lowers the value across the timeline and holds around 5% in municipal solid waste.

Date	Paper	Plastic	Bio
2021/09	5.62%	11.41%	25.47%
2021/11	5.05%	8.09%	35.78%
2022/04	3.27%	3.65%	34.97%
2022/05	4.44%	3.29%	22.08%

Table 5-11 Database - 3. cluster

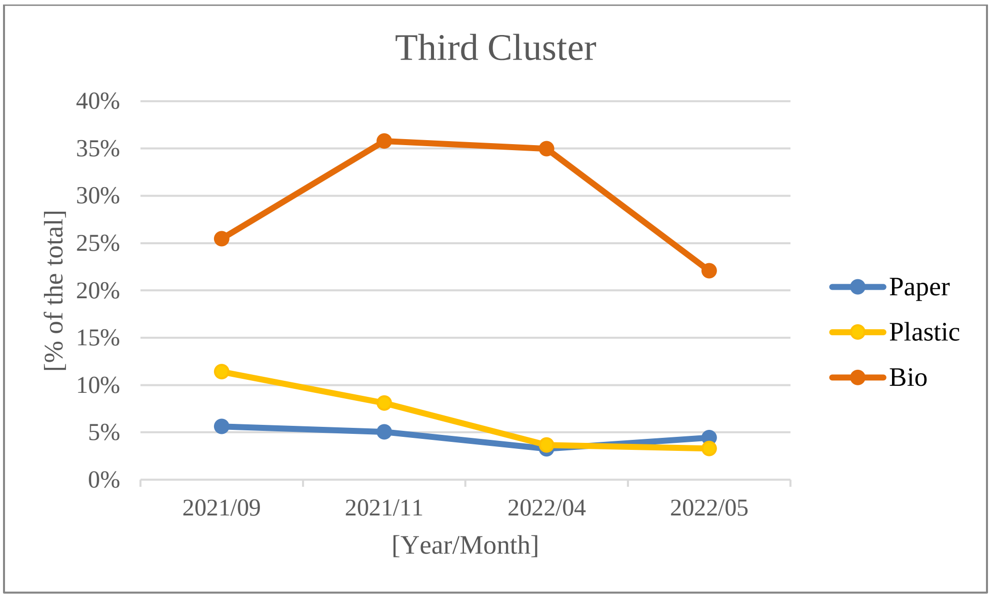

Figure 5-39 Changes in paper, plastic, biodegradable waste streams - 3. cluster

- Fourth cluster

The fourth presented cluster is specified by the following characteristic patterns:

- Former district centres/cities
- Population: On average 10 000 inhabitants (minimum: Number of thousands, maximum: 22 000 inhabitants)

According to Table 5-12 and Figure 5-40, results from the fourth cluster show high values for the Paper and Plastic streams. Both streams record value of around 10%, where the final recorded value for both streams in May 2022 is close to 9% in municipal solid waste. The biodegradable waste stream records its maximum value in November 2021 at 33% and in the next month the lowest value of 23% of the total municipal solid waste.

Date	Paper	Plastic	Bio
2021/09	8.38%	10.70%	28.42%
2021/10	6.91%	14.79%	30.90%
2021/11	10.52%	13.88%	32.55%
2021/12	12.19%	8.38%	22.60%
2022/05	8.79%	8.71%	30.21%

Table 5-12 Database - 4. cluster

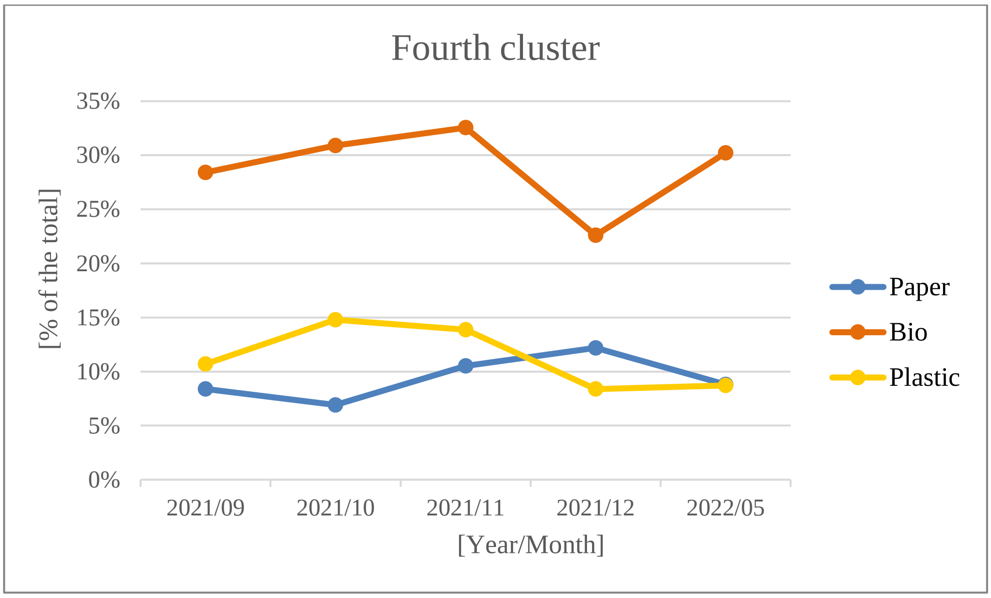

Figure 5-40 Changes in paper, plastic, biodegradable waste streams - 4. cluster

- Fifth cluster

The Fifth presented cluster is specified by the following characteristic patterns:

- Former district centres/cities
- Population: maximum of 10 000 inhabitants

As Table 5-13 and Figure 5-41 show, the Fifth presented cluster shares similar patterns with the fourth cluster except for the maximum number of inhabitants. In comparison with the results from the fourth cluster, the fifth cluster reports lower values for the Plastic and Paper stream, where the value for both streams does not exceed 5% in the years 2019 and 2020. The plastic stream shows the smallest value of the monitored streams with a maximum value of 7.2% recorded in November 2021. In the same month, paper records the maximum value of 10.6% in municipal solid waste. The biodegradable waste stream in the fifth cluster can be described as stable and with similar values as in the general municipal solid waste analysis.

Datum	Paper	Plastic	Bio
2019/09	4.43%	4.60%	30.44%
2019/11	5.00%	4.57%	32.69%
2019/12	4.34%	3.73%	32.95%
2020/01	2.89%	3.50%	24.20%
2020/03	4.41%	3.97%	25.28%
2021/11	10.61%	7.17%	29.87%
2021/12	8.44%	5.79%	32.36%
2022/02	7.59%	6.70%	26.40%

Table 5-13 Database - 5. cluster

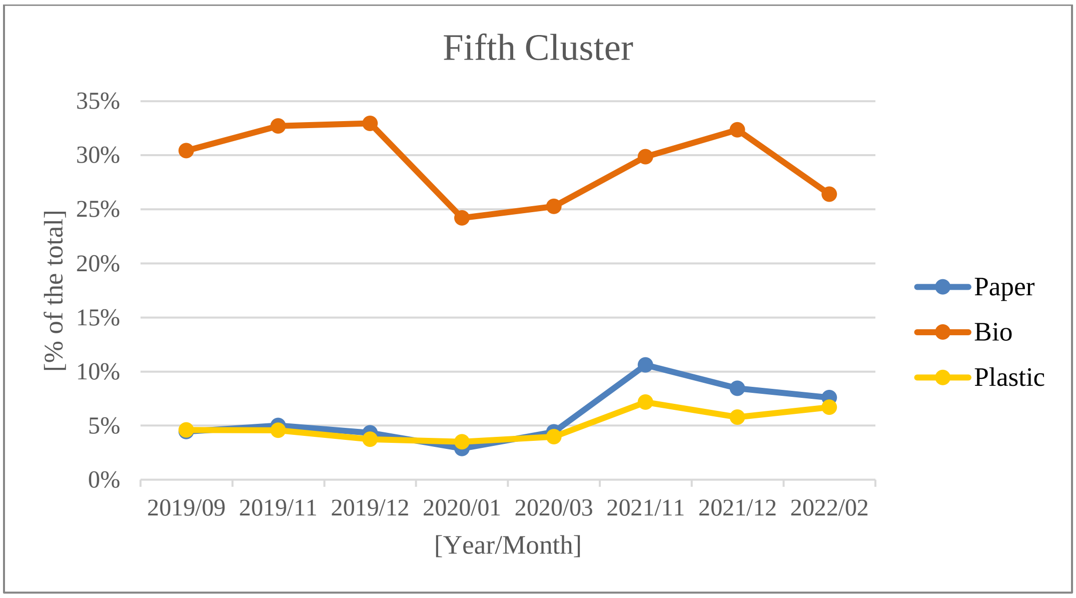

Figure 5-41 Changes in paper, plastic, biodegradable waste streams - 5. cluster

- Sixth cluster

The sixth presented cluster is specified by the following characteristic patterns:

- Countryside type of households
- Lower population density
- High concentration of holiday resorts

According to Table 5-14 and Figure 5-42, results in the sixth cluster show stable values of the paper and plastic streams. Plastic stream's value ranges from 4.5 to 7.5% in municipal solid waste. The paper stream oscillates around the value of 5% in municipal solid waste. The first value of the biodegradable waste stream of 44% is the highest recorded value during the monitored time. The lowest value of 24% for the biodegradable waste stream was recorded in April 2022. The average mean value during the monitored time of the biodegradable waste stream is 31%. The results can be described as expectable in connection to the type of cluster and results from the general municipal solid waste analysis.

Date	Paper	Plastic	Bio
2021/09	6.22%	7.44%	44.01%
2021/10	5.32%	6.94%	32.41%
2021/11	2.63%	4.47%	29.32%
2022/02	4.02%	4.49%	28.26%
2022/04	3.32%	4.45%	24.03%
2022/05	4.11%	4.65%	29.02%
2022/06	6.98%	7.01%	31.38%

Table 5-14 Database - 6. cluster

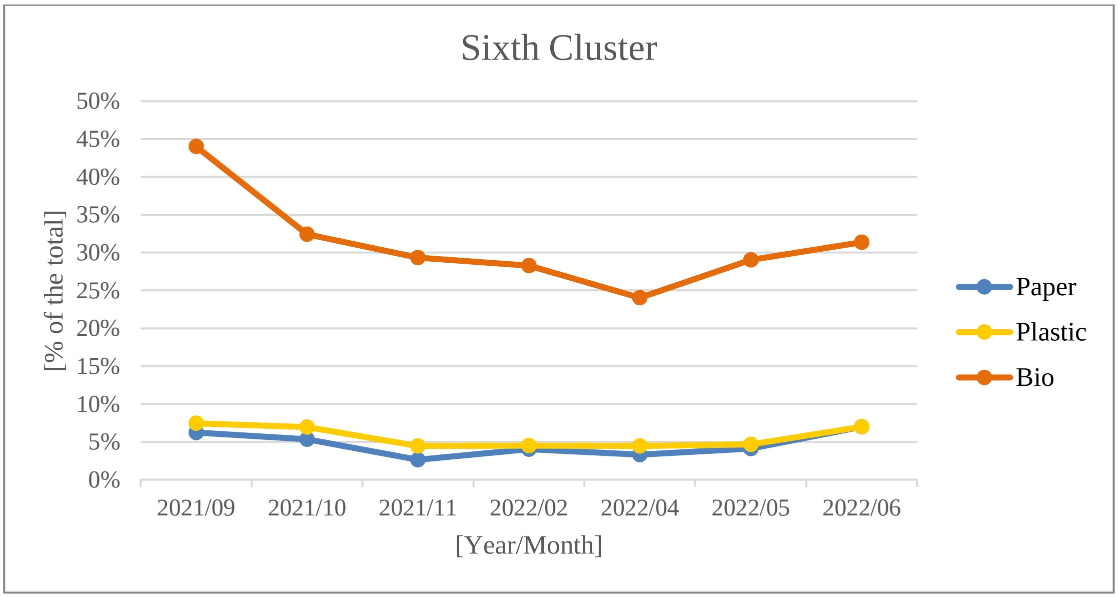

Figure 5-42 Changes in paper, plastic, biodegradable waste streams - 6. cluster

- Seventh cluster

The seventh presented cluster is specified by the following characteristic patterns:

- Countryside type of households
- Low population density

As Table 5-15 and Figure 5-43 show, the results presented for the seventh cluster are similar to the results from the sixth cluster. A paper stream represents a small part of municipal solid waste with an overall average mean value of 2.91%. Plastic stream shows the stability of the stream during the measured time with an average mean value of 5% in municipal solid waste. During the first 3 measured months, the biodegradable waste stream shows high values of over 35% in the municipal solid waste. In the next measurements, the value of the biodegradable waste stream drops below 20%. The calculated results meet the assumptions given by the specification of the cluster, where the biodegradable waste stream should be holding the greatest value with possible high drops due to specific factors of the examined households. Lower values of the paper and plastic stream in comparison with the sixth cluster can be due to the “high concentration of holiday resorts” specification.

Date	Paper	Plastic	Bio
2021/08	3.35%	6.62%	43.20%
2021/09	4.65%	5.67%	35.91%
2021/10	1.03%	2.03%	37.94%
2021/11	4.21%	4.92%	16.59%
2022/04	1.34%	5.83%	19.24%

Table 5-15 Database - 7. cluster

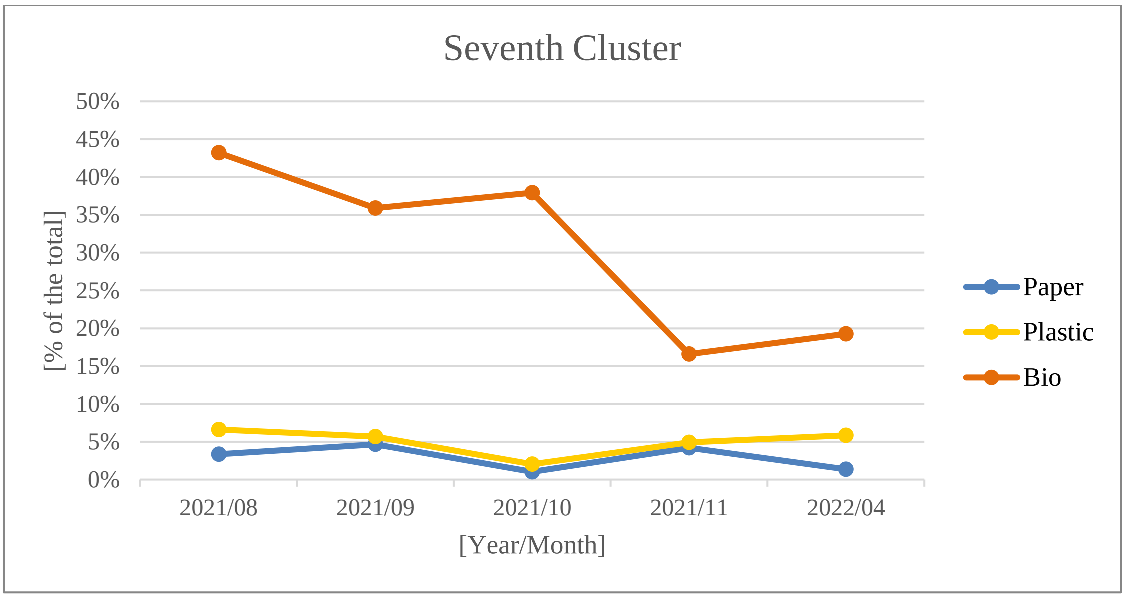

Figure 5-43 Changes in paper, plastic, biodegradable waste streams - 7. cluster

- Eighth cluster

The Eighth presented cluster is specified by the following characteristic patterns:

- Countryside type of households
- High population density
- The high amount of work travellers

According to Table 5-16 and Figure 5-44, results given for the eighth cluster show the stability of followed streams with an exception in deviation for the biodegradable waste stream in May 2022. The deviation shows a drop in value of almost 30%. This deviation shows the uniqueness of each sample. The explanation for the deviation can be done by the usage of the following levels of solid waste analysis. Without the deviation, the biodegradable waste stream reports a value of around 35% of the total municipal solid waste during the following time. The plastic stream value ranges between 3.5% to almost 8% of the total municipal solid waste. The paper stream reports low values during the following time with February 2022 being the only month to exceed 5% with the value of 7.7% of the total municipal solid waste.

Date	Paper	Plastic	Bio
2021/09	5.04%	4.48%	36.27%
2021/10	3.62%	3.47%	37.10%
2021/12	3.72%	4.13%	30.83%
2022/01	4.56%	6.96%	29.97%
2022/02	6.78%	7.68%	38.15%
2022/04	2.20%	5.55%	42.69%
2022/05	1.84%	3.62%	6.02%

Table 5-16 Database - 8. cluster

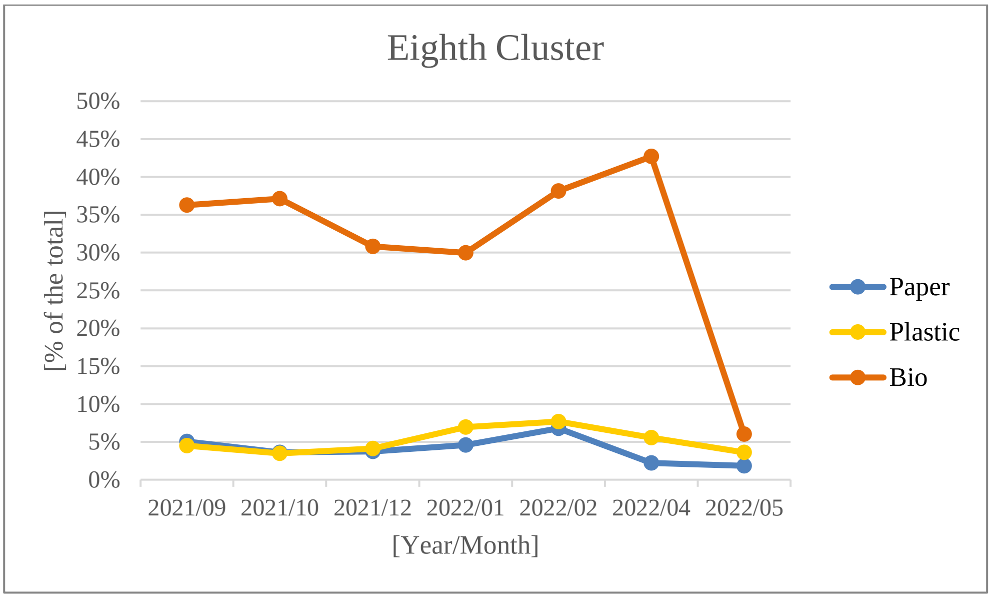

Figure 5-44 Changes in paper, plastic, biodegradable waste streams - 8. cluster

- Ninth cluster

The ninth presented cluster is specified by the following characteristic patterns:

- Countryside type of households
- High population density

As Table 5-17 and Figure 5-45 show, Results from the last presented cluster show a rising trend in the paper and plastic streams and instability of the biodegradable waste stream. In the first two examined months, September and October 2019, the biodegradable waste stream reports the highest values across all the studied clusters, accounting for almost 60% of the total municipal solid waste. In the subsequent months, the biodegradable waste stream shows a significant decrease in value in comparison to the previous results. The value drops to almost half of the value from the first two examined months, with only 22% of the total municipal solid waste composed by the biodegradable stream in February 2020. The paper stream grows in value during the following time, where the value starts at 4.9% in September 2019 and finishes at 7.5% of the total municipal solid waste in February 2020. The plastic stream copies the paper stream with the growing trend and the resulting values across the observed time. The exception for the plastic stream comes in October 2019 with a drop in value to 3% of the total municipal solid waste. The significant change in the value of the biodegradable waste stream can be caused by implementations and changes given by the new waste management strategy of the municipality. High results for the biodegradable waste and results for the paper and plastic stream fluctuating around 5% are expected in connection to the specification of the cluster and results from the general solid waste analysis.

Date	Paper	Plastic	Bio
2019/09	3.10%	4.83%	52.49%
2019/10	4.44%	3.00%	59.55%
2019/11	7.12%	5.68%	27.73%
2020/02	7.63%	7.25%	21.70%

Table 5-17 Database - 9. cluster

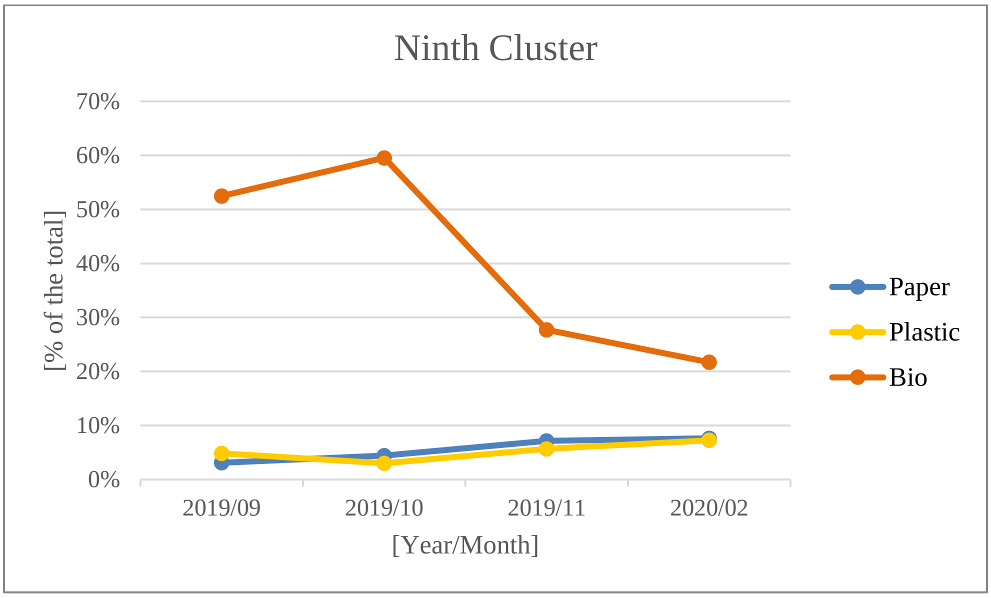

Figure 5-45 Changes in paper, plastic, biodegradable waste streams - 9. cluster

CONCLUSION OF THE MUNICIPALITY-BASED ANALYSIS

The analysis shows changes in the composition of municipal solid waste in nine studied clusters. The first and second clusters can both be specified as municipalities with high populations and report the highest instability of followed streams with several peaks and lows from all the studied clusters. Biodegradable waste stream has a rising trend over the given time. Under the fourth and fifth cluster falls municipalities which have a maximum of 10 000 inhabitants. Both clusters declare waste stream values which oscillate but are stable without any significant peaks. The sixth to ninth clusters can be described as countryside municipalities. All the countryside clusters have stable paper and plastic streams without any significant changes over the following time. The biodegradable waste stream of countryside clusters is stable but differs in value, which is dependent on the type of household and the waste collection logistics in the municipality. A common option for countryside households is home biodegradable waste recovery inform of composting. Based on the infield sorting experience, peaks and drops of the biodegradable waste stream for the countryside cluster can be caused by specific types of representative samples, which would be mainly composed of non-standard waste streams.

6 CASE STUDY

The diploma thesis introduced a connection between waste management and waste composition analysis. In the theoretical part, the thesis mentioned possible different approaches towards the methodological part of the waste composition analysis. To allow a closer look at the introduced methodology and understanding of the use of the waste composition tool and possible achievable goals, the case study of municipal solid waste analysis for a chosen municipality was created.

The case study follows the Czech municipal solid waste analysis methodology – TIRSMZP 719. The methodology was introduced in the theoretical part of chapter 3.1.2. The first step in the performance of solid waste analysis is the collection of samples. The process of collection and information about the representative sample are described in chapters 3.1.2 and 5.1. The representative sample is formed by waste containers with a volume of 1,100 litres or by 1 m^3 of unmodified municipal solid waste. The required volume can be obtained by a combination of the smaller container's volume. Important information should be mentioned, the volume of waste containers does not equal the volume and amount in kilograms of generated municipal solid waste. As the methodology recommends, to be able to track and follow trends and stability of waste streams, the waste composition analysis should be performed at least 4 times per year. Each analysis should cover one season of the year. The solid waste analysis in the chosen municipality was conducted between August 2019 and March 2022. The gap in the sample's records between March 2020 and August 2021 is due to the complications connected with the pandemic situation of COVID-19 [28].

The case study is carried out with data for the municipality Brno, which belongs to the first cluster. The specifications of the municipality allow further progress in connection to waste management with the results given by the municipal solid waste analysis. The waste analysis revealed that biodegradable waste has the highest values in total solid waste. The Biodegradable waste stream ranges between 15% and 34%. The average value of the biodegradable waste stream over the following time is 23.17%. Around 28% of municipal solid waste is composed of a fine proportion. The category of different waste is the third most represented stream with an average value of 21.31% during the following timeline. Paper and plastic streams belong between followed streams due to their recycling potential and established separated collection process. The value of the paper stream ranges between 7.2% to 15.11% with an average value of 10.03% over the following time. The value of plastic stream ranges between 5.33% and 12.25% with an average value of 8.74%. The average value of total fine proportion, which is the sum of fine proportion under 40-, 20- and 10-mm mesh, is almost 27%.

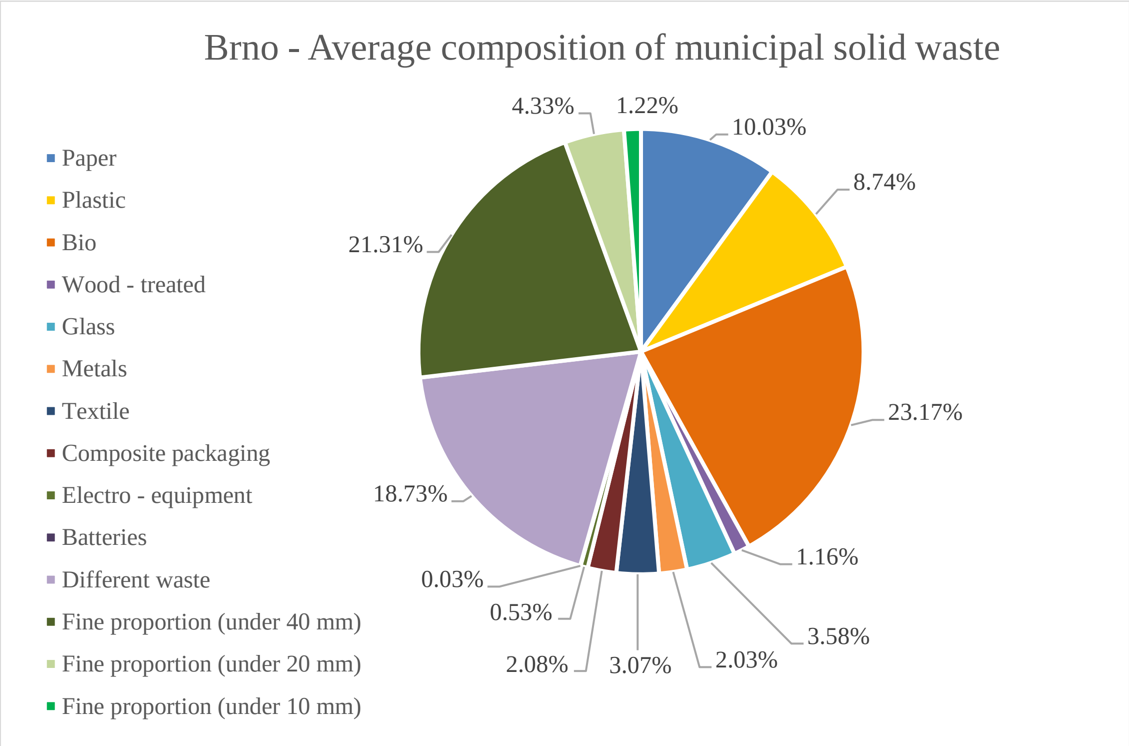

Figure 6-1 – Average composition of municipal solid waste Brno

As the results in Figure 6-1 and Figure 6-2 show, paper, plastic, and biodegradable waste streams in municipal solid waste hold potential for future recycling or reuse with a selected type of waste treatment. To gain a better understanding of the municipality results, the results of each stream in the third level of the solid waste analysis are used. The following figure describes the development of production over the following time of chosen waste streams in the studied municipality.

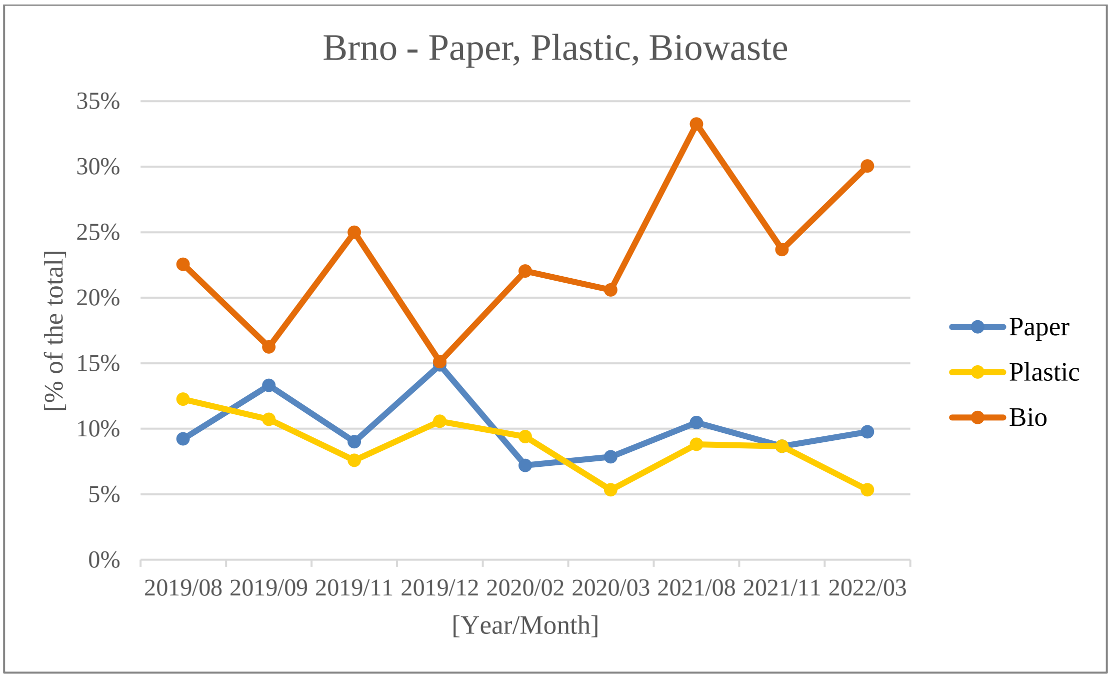

Figure 6-2 Changes in followed streams over time in Brno

The biodegradable waste stream reports a small rising trend during the following timeline. As the results of the general third-level waste composition analysis in the third level show, more than one-third of the total biodegradable waste stream is composed of other food fractions. As defined by the methodology, the other food fraction is made of whole, unwrapped, leftover processed food, unprepared side dishes, tea bags, bones and peels. The average value of the other food is 37.07% in the biodegradable waste stream. Figure 6-3 shows the other food fraction.

Figure 6-3 The other food fraction

Residues from the preparation of fruit and vegetable accounts for 28.18% of the biodegradable waste stream. As defined by the methodology, the fraction is made of cuttings, peels, stems and leaves of vegetables, and squeezed citrus fruits. Figure 6-4 shows the residues from the preparation of fruit and vegetable fraction.

Figure 6-4 Residues from the preparation of fruit and vegetable fraction

The fruit and vegetable, which has not been modified or used, fraction creates on average 14.49% of the biodegradable waste stream. As defined by the methodology, the fraction is made of whole fruit and vegetables, including spoiled ones. Figure 6-5 shows the fruit and vegetable, which has not been modified or used, fraction.

Figure 6-5 The fruit and vegetable, which has not been modified or used, fraction

The remaining 20.25% is made up of the garden-produced biodegradable waste fraction. As defined by the methodology, the fraction is made of grass, branches from tree trimming or felling (wood), leaves, soil, plants and weeds, and used plant-based pet bedding. Figure 6-6 garden-generated biodegradable waste fraction.

Figure 6-6 Garden-generated biodegradable waste fraction

Given the assumption of composition and the results of the municipality's waste composition analysis, the recommendation is for treatment with anaerobic digestion in the biogas plant, which will generate energy and other possible products from the biodegradable waste. Figure 6-7 shows the average composition of the biodegradable waste stream.

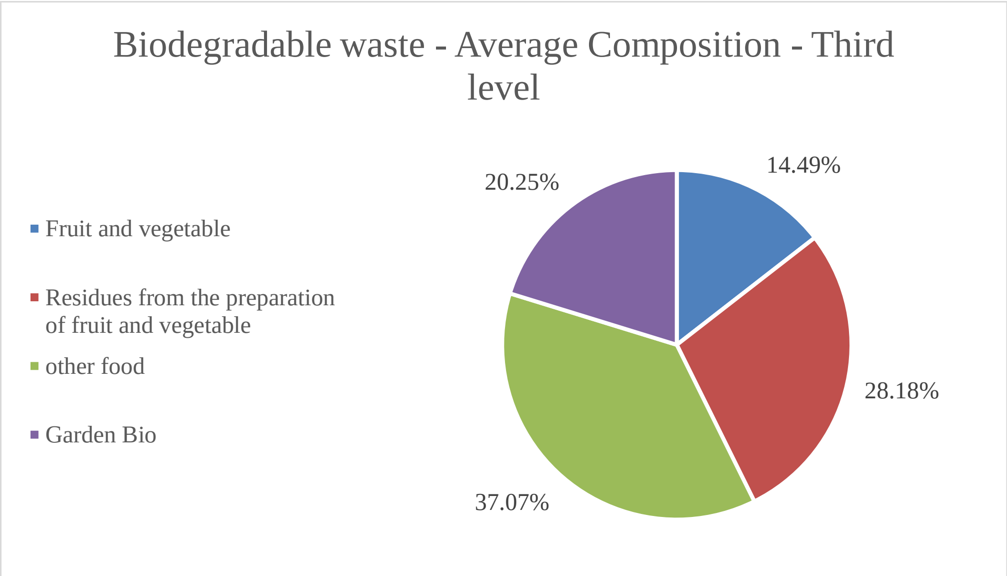

Figure 6-7 Biodegradable waste - Average Composition

In comparison to the aerobic digestion processed in the composting facility, the biogas plant is more suitable for a heterogeneous mixture of the studied biodegradable waste stream. The following options for the biogas plants were established with taking into account the specification about the cluster being a regional city. Data about the yearly collected waste comes from a waste treatment company SAKO Brno, which deals with waste disposal in the regional city of Brno [30].

Year	2018 [t]	2019 [t]	2020 [t]	2021 [t]	2022 [t]	Average [t]
Municipal solid waste	68,805	67,997	69,469	68,899	66,331	**68,064**
Paper	9,972	8,769	7,979	7,776	7,549	8,542
Glass	4,137	4,283	4,861	5,042	4,907	4,400
Plastic	3,209	3,460	3,819	3,943	4,102	3,397
Textile	480	394	510	500	512	493
Biowaste - collected	117	138	166	1,010	1,491	584
Sum	86,720	85,041	86,804	87,170	84,892	85,315

Table 6-1 Amount of collected waste by SAKO Brno

Table 6-1 shows the amount of collected waste through categories of municipal waste. For the calculation was used an average value of 68,064 tonnes of collected municipal solid waste. This value was multiplied by the average percentage of biodegradable waste in the researched municipality 23.17%, which was presented earlier in the chapter. After the calculation, the generated amount of biodegradable waste is 15,770 tonnes per year in the studied municipality. Table 6-2 connects this amount with the presented composition of the biodegradable waste.

Brno	Percentage	tonnes/year
Fruit and vegetable	14.49%	2286
Residues from the preparation of fruit and vegetable	28.18%	4445
other food	37.07%	5847
Garden Bio	20.25%	3193
Biodegradable waste from MSW	100%	15770

Table 6-2 Possible income of biodegradable waste

Based on the information given by the article "Using biogas from municipal solid waste for energy production: Comparison between anaerobic digestion and sanitary landfilling", the expected production of biogas from the biodegradable waste of volume rate of 1.8 tonnes per hour is 286.6 normal m^3 per hour and the lower heating value of the biogas generated from biodegradable waste is 19 megajoules per normal m^3. The presented amount of produced biogas corresponds to the calculations also in comparison with real biogas plants in Vyškov and Rapotín. Both biogas plants use biodegradable waste as a source for anaerobic digestion. Table 6-3 shows information about the produced biogas from municipal solid waste [21], [22], [31].

Brno - Biogas feedstock information		
Municipal solid waste – SAKO Brno	68,064.00	tonnes/year
Municipal solid waste – SAKO Brno	7.77	tonnes/hour
Avrg. Biowaste in MSW - Brno	23.17	%
Biowaste from MSW	15,770.43	tonnes/year
Biowaste from MSW	1.80	tonnes/hour
Produced biogas	286.60	Nm3/hour
Amount of CH4 in biogas	56.00	%
Amount of CO2 in biogas	44.00	%

Table 6-3 Information about the produced biogas

Two potential variants of cogeneration units were designed for the biogas produced by the facility: the Flexi 430 and Flexi 530 units, both of which are designed for biogas combustion and produced by TEDOM. Table 6-4 shows the maximal feed capacities for the cogeneration unit 206.8 normal m^3 per hour for the first variant and 248.9 normal m^3 per hour for the second variant. The excess biogas can be stored in reservoirs or subjected to a purification process with the aim of obtaining biomethane. The assumed lover heating value of produced biogas is 19 MJ per normal m^3. With the assumed operating time of 8,000 hours, the investment into a biogas station can yearly generate 3,440 MWh of electric power and 4,400 MWh of thermal power with Flexi 430 and 4,224 MWh of electric power and 5,112 MWh of thermal power with Flexi 530 [23], [32].

	1. variant	*2. variant*	
Name	*Flexi 430*	*Flexi 530*	
LHV of biogas	19	19	MJ/Nm3
Max. biogas feed	206.8	248.9	Nm3/h
Biogas left	79.8	37.7	Nm3/h
Thermal Power of Cogeneration	550	639	kWh
	4,400	5,112	MWh/year
Thermal efficiency	50.5	46.6	%
Electric Power of Cogeneration	430	528	kWh
	3,440	4,224	MWh/year
El. Efficiency	39.4	40.2	%
Operating time	8,000	8,000	hours

Table 6-4 Variants of the cogeneration units

The results shown in Table 6-4 should be taken as indicative, as the calculations do not consider the local losses associated with the anaerobic digestion process or losses in the cogeneration unit. The procedure for obtaining the results for material recovery of the biodegradable waste stream is shown in Figure 6-8.

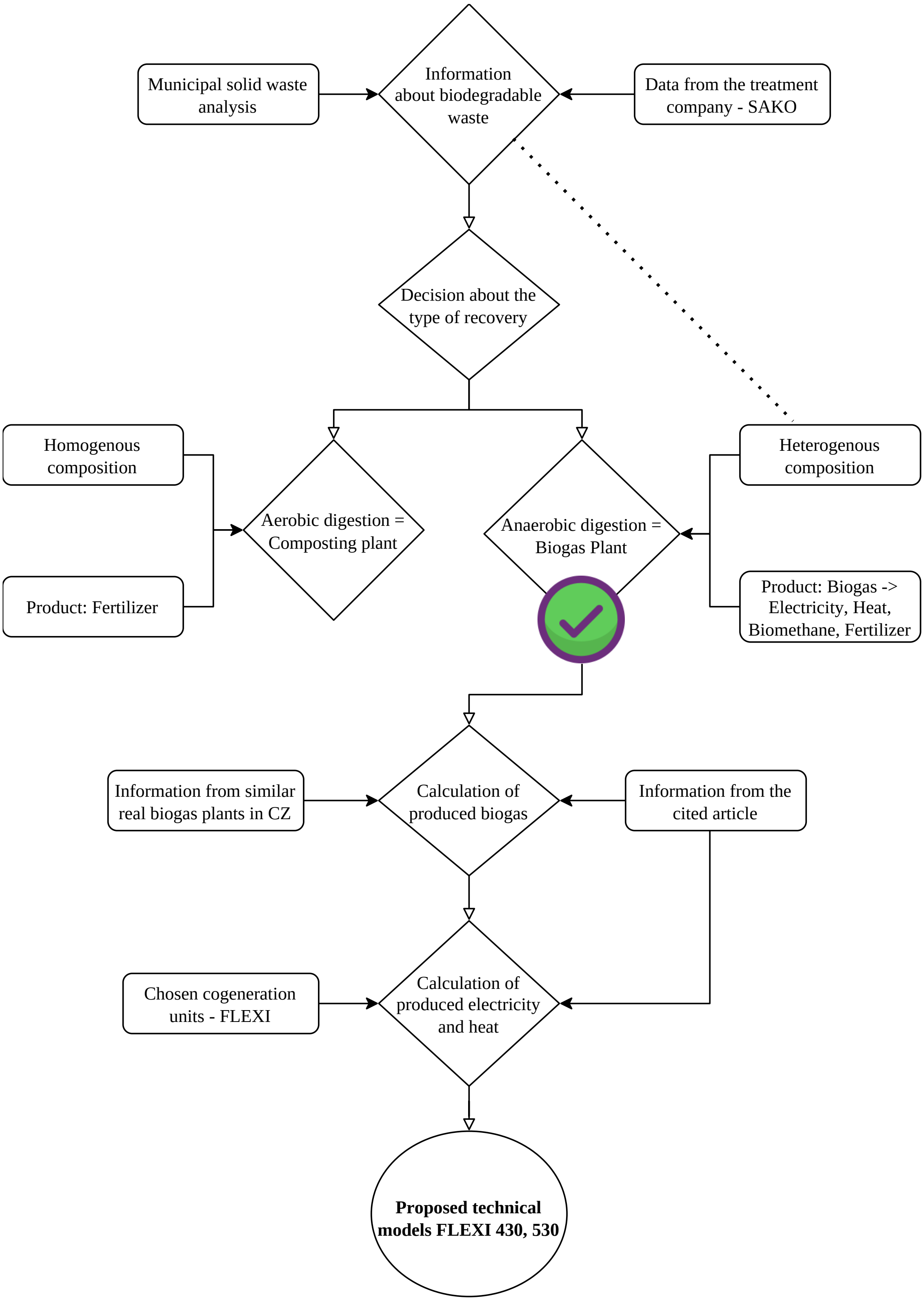

Figure 6-8 Technological procedure of the case study

The plastic stream accounts for 8.7% of the total municipal solid waste in the studied municipality. In connection with the studied third level of the plastic stream, more than half of the stream is made of the Wraps and Bags fraction. The hard plastic fraction represents 26.6% and the PET fraction is only 8.5% of the total plastic stream in the total municipal solid waste.

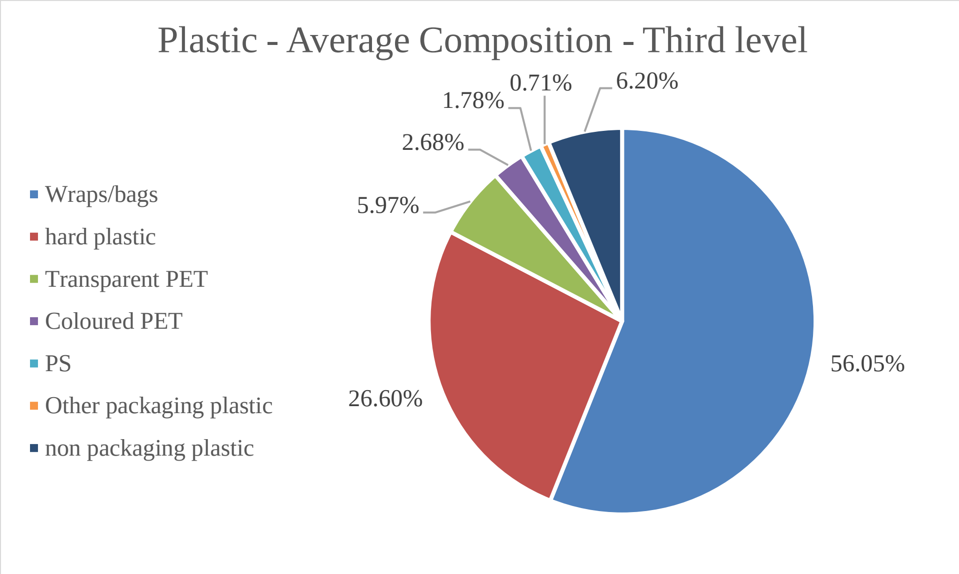

Figure 6-9 Plastic - Average Composition - Third level

Plastic streams can be in the future affected by the deposition system for PET. According to Figure 6-9, the PET fraction value in the studied municipality is 0.76% of the total municipal solid waste. As shown in Table 6-5, in connection with values obtained from SAKO Brno, the weight of produced PET fraction in municipal solid waste is 515 tonnes per year. These values can be potentially removed with the start of the deposition system, which would lead to a smaller amount of generated municipal solid waste[30].

	Percentage	tonnes/year
Municipal solid waste	-	68,064
Plastic in the MSW - Brno	8.74%	5,948
Transparent PET	5.97%	355
Coloured PET	2.68%	160
Total PET	8.66%	**515**

Table 6-5 Possible income of plastic in Brno

The paper stream accounts for 10% of the total municipal solid waste in the studied municipality. In connection with the studied third level of the paper stream, more than one-third of the stream is made of cardboard fraction with a value of 37.9%. The magazine's fraction represents around 20% and the other packaging paper fraction is 17.4% of the total paper stream in the total municipal solid waste. The average composition of the paper stream is shown in Figure 6-10.

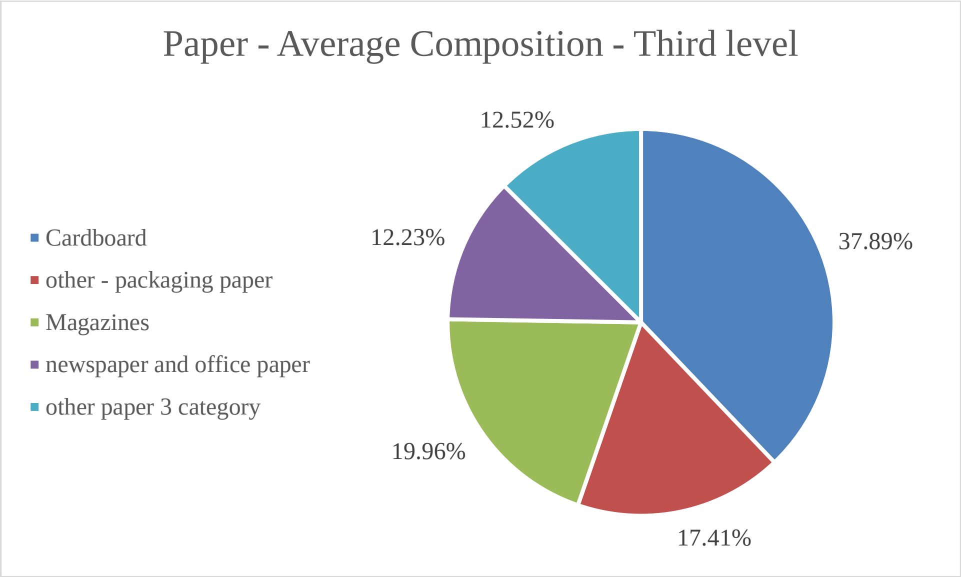

Figure 6-10 Paper - Average Composition - Third level

The goal of the municipality's waste management executive should be to minimise the paper and plastic stream in municipal solid waste. The aim can be achieved through the use of sorting lines from municipal solid waste or through increased recycling education in conjunction with a possible increase in the frequency of recycling containers.

Over a quarter of the total municipal solid waste is composed of a total fine proportion. Based on the experience gained during the infield sorting and data collection process, it has been observed that the fine proportion of waste is characterized by a high concentration of organic matter, which rises its potential for material recovery technologies.

Figure 6-11 Fine proportion

As can be seen in Figure 6-11, a typical composition of fine proportion contains smaller particles and organic residues. Due to gained information about the composition of fine proportion, the fine proportion can be connected to the biodegradable waste stream as a feedstock for designed biogas plants.

RESULTS OF THE CASE STUDY

The case study presents solutions for chosen waste streams of municipal solid waste with a high potential for waste recovery. The case study has been prepared for the municipality from the first cluster – Brno. Table 6-6 introduces the weight amount for the studied waste streams, where the percentage values were obtained from waste composition analysis for the chosen municipality and the weight value for the municipal solid waste was obtained from SAKO Brno.

Brno - Average	Percentage of MSW	tonnes per year
Paper stream	10.03%	6,830
Plastic stream	8.74%	5,948
Bio stream	23.17%	15,768
Municipal solid waste	100%	68,064

Table 6-6 Weight of studied streams in Brno

Due to the connection with data available from SAKO Brno about separately collected waste and data in the previous table, Table 6-7 presents a possible decrease in generated municipal solid waste with the implementation introduced by the case study.

Brno SAKO - Year	Average [tonnes]	Average after implementation. [tonnes]
Municipal solid waste	**68,064**	**39,518**
Paper separately collected	8,543	15,372
Glass separately collected	4,400	4,400
Plastic separately collected	3,397	9,345
Textile separately collected	494	494
Biodegradable waste - collected	584	16,352
Material Recovery (SUM except MSW)	**17,418**	**45,964**

Table 6-7 Impacts of potential waste recovery implementation

The biodegradable waste is recommended for a separate collection process. Separately collected biodegradable waste shall be utilised in biogas plants due to its diverse composition and the high percentage of other food fraction. The case study prepared a technical model of a biogas plant which will use biodegradable waste as a feedstock. The fine proportion of municipal solid waste is also suitable as a feedstock for the biogas plant due to the high concentration of organic residues in its composition. Biogas plant falls under the material recovery category and as a product produces biogas. Biogas can be as fuel for the cogeneration unit, which is used for the generation of electricity and heat or can be cleaned into biomethane. Biogas can be used depending on market demand. For the plastic and paper stream is presented implementation in the form of a sorting line and higher social awareness. As a potential source for material recovery not included in the calculation can be used the fine proportion due to the high concentration of organic residues in its composition. Figure 6-12 sums up values presented in the previous table about the implemented plan for waste management of municipal solid waste.

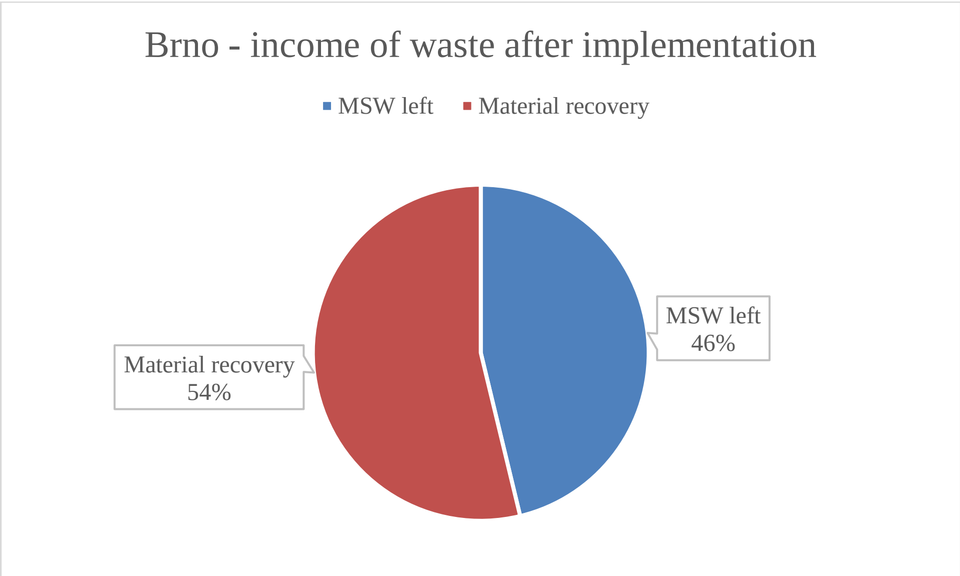

Figure 6-12 Amount of generated MSW after suggested implementations

The steps presented shall lead towards a higher percentage of reuse and recycling of the given waste streams and a reduction in the value of the produced municipal solid waste. A lower amount of produced municipal solid waste is a prerequisite for a lower amount of waste disposed of by landfilling therefore, the recommended implementation brings the municipality closer to the achievement of separation goals of Czech waste management for the coming years and brings the municipality into the circular economy model.

7 DISCUSSION

Discussions are used to think about topics related to the dissertation and topics that resonate in society in the context of waste management.

- Achievement of goals set by Waste Act 541/2020

The Waste Act sets targets related to waste treatment methods. The aim is to obtain 65% of the municipal waste's weight for waste recovery in 2035. No more than 10% of total municipal waste's weight can be disposed of by landfilling by 2035. In connection with energy utilization, in 2035 maximum of 25% of total municipal waste's weight can be energetically utilized. The solid waste analysis reveals the potential of municipal solid waste for different types of waste treatment than landfilling and energy recovery by the waste-to-energy plant. The highest potential holds the biodegradable waste stream, occurring in municipal solid waste with an average mean value of almost 30% of total municipal solid waste. In connection with the separated collection, the biodegradable waste stream can be treated through anaerobic or aerobic digestion. The paper and plastic stream has an average mean value of around 7% of the total municipal solid waste. The aim of waste management should be to transfer these waste streams from municipal solid waste to the appropriate separated and collected municipal waste streams. In the ideal scenario of recovery of chosen waste streams with all the presented values (Biodegradable waste stream 30%, Paper and plastic stream 6%) the percentage of municipal solid waste in municipal waste would decrease to almost 28%. This decrease would automatically come with an increase in value in waste recovery and a decrease in the value of waste disposed in landfills. The decisions based on solid waste analysis would lead Czech waste management towards the set targets. Table 7-1 describes the production of municipal and municipal solid waste in the Czech Republic [10].

Czech Republic	Total municipal waste production [t]	Total municipal solid waste production [t]	Percentage of MSW in municipal waste
2019	5,879,163	2,787,356	47%
2020	5,729,917	2,780,347	49%
2021	5,904,434	2,755,893	47%

Table 7-1 Czech Republic Municipal solid waste production

- Deposit system for PET

Among the hot topics connected with waste management belongs the introduction of a deposit system for bottles made of polyethene terephthalate (PET bottles). One of the arguments related to this issue is the possibility that PET bottles do not end up in municipal solid waste. With the help of solid waste analysis, it can be seen, that the value of PET fraction is only 8.5% of the total plastic stream which is 0.5% of the total municipal solid waste. The solid waste analysis shows that the PET fraction in municipal solid waste holds a low potential value for recycling and it can be assumed that the fraction is well recycled in the Czech Republic. The deposit system for PET would make a small difference in the composition of municipal solid waste but it would have a higher impact on the separately collected plastic waste stream [33].

- Potential of Dry Mixed Recycling (DRM)

Dry Mixed Recycling is an alternative waste collection and utilization of selected materials which are suitable for material recovery. DRM is an established recycling technique in Great Britain which tries to make recycling as straightforward as possible by using one separate waste bin for clean dry recyclables instead of many variants of waste bins for each recycled waste stream. Into clean dry recyclables and the same Dry Mixed Recycling bin belong [34]:

- Empty metal cans – drinks, food, aluminium foil, aluminium food containers
- Plastics – bottles, cups, milk, packaging
- Cardboard – boxes, greetings cards, brown paper
- Paper – plain white, newspaper, magazines, shredded paper

The introduction of DRM can potentially increase the amount of recycling. As the municipal solid waste analysis showed, waste streams available for DRM together account for about 15% of total municipal solid waste. DRM can potentially reduce the amount of generated municipal solid waste which would result in a reduction of waste sent to landfills, which is the main idea behind DRM. As noted, DRM can have a positive impact on the separation goals by increasing recycling amount and reducing landfilling. It should be mentioned that DRM should not replace the existing system as there is no recycling of the glass waste stream [34].

8 CONCLUSION

The main theme of this master thesis is the right use of waste composition analysis which will help waste management to be in respect with the principles of the circular economy. This theme has complied with the following aims for the thesis. The first aim is an introduction to waste problematics and an understanding of the principles of waste composition analysis. The main practical goal is to use the obtained raw data from the solid waste analysis and recalculate them into usable results for waste management. For accomplishing practical goals, the programming script for the data processing shall be developed. As a last aim of the thesis, a case study which uses the tool of waste composition analysis with the connection of waste treatment recommendations shall be presented.

The theoretical part at the start introduces the topic of waste management, continues with the definition of municipal solid waste in connection with the thesis theme, and subsequently describes waste legislation valid for the European Union and the Czech Republic. An important topic for the thesis is the circular economy, in which goals and ideology have been described. Shift towards a circular economy can be taken as one of the main challenges of waste management. These challenges bring the need for decisions based on historical data on the development of municipal waste, which can be obtained through waste composition analysis. The theoretical part introduces waste treatment methods, which relate to the field studied in the thesis. The thesis closes the theoretical part with a description of the waste composition analysis methodologies – Solid Waste Analysis (SWA) Tool established by the European Commission and Czech certified methodology created by the Institute of Process Engineering from Brno University of Technology within the project TIRSMZP719.

The practical part starts with describing the process of obtaining the raw data of the solid waste analysis based on the established Czech certified methodology TIRSMZP719. The first process of the waste composition analysis is the collection of the representative sample. Afterwards, the sample is sorted into introduced waste streams and fractions. Both processes are described by the certified methodology. Data about the sorted sample are written into Excel. To be able to follow changes in given waste streams in municipal solid waste and find their average value over the monitored timeline, a script through Visual Basic Application (VBA) for Excel has been programmed. The script allows filtration and recalculation of values from the raw database, where the results show weighted arithmetic values of given waste streams and fractions in the first and third levels of the waste composition analysis. The script also allows the user to filter the data depending on the chosen municipality, where the waste composition analysis has taken place. For each result has been created diagrams where can be found trends of studied waste streams. The results show a high concentration of the biodegradable waste stream in the municipal solid waste. The value on average is around 30% of total municipal solid waste. Such an amount holds high potential for recovery processes, where between the most popular for biodegradable waste belongs to aerobic and anaerobic digestion. Paper and plastic streams in municipal solid waste also hold potential for waste recovery processes.

The chosen municipality case study introduces the results of the waste composition analysis on the first level. Afterwards, the case study connects the knowledge gained from the practical part about the third level of studied waste streams with the presented results. This connection allows for recommendations on waste treatment technologies, where the thesis presents two possible solutions for a biogas plant, which would use biodegradable waste. Such a solution would lead to the reduction of generated municipal solid waste and waste stored in landfills and therefore into a safer environment. Plastic and paper streams shall be separated by sorting lines or shifted into their separately collected waste containers due to due to society's increased awareness. Implementation of the presented solutions of the case study for the biodegradable, plastic, and paper streams will lead to a reduction of generated municipal solid waste to almost half of its original value if the entire available value potential in the streams concerned is used. In the context of the Czech waste management targets, municipal solid waste would represent only 28% of municipal waste. The decrease in the value of municipal solid waste will lead to an increase in recycling and material recovery, bringing Czech waste management closer to the circular economy model.

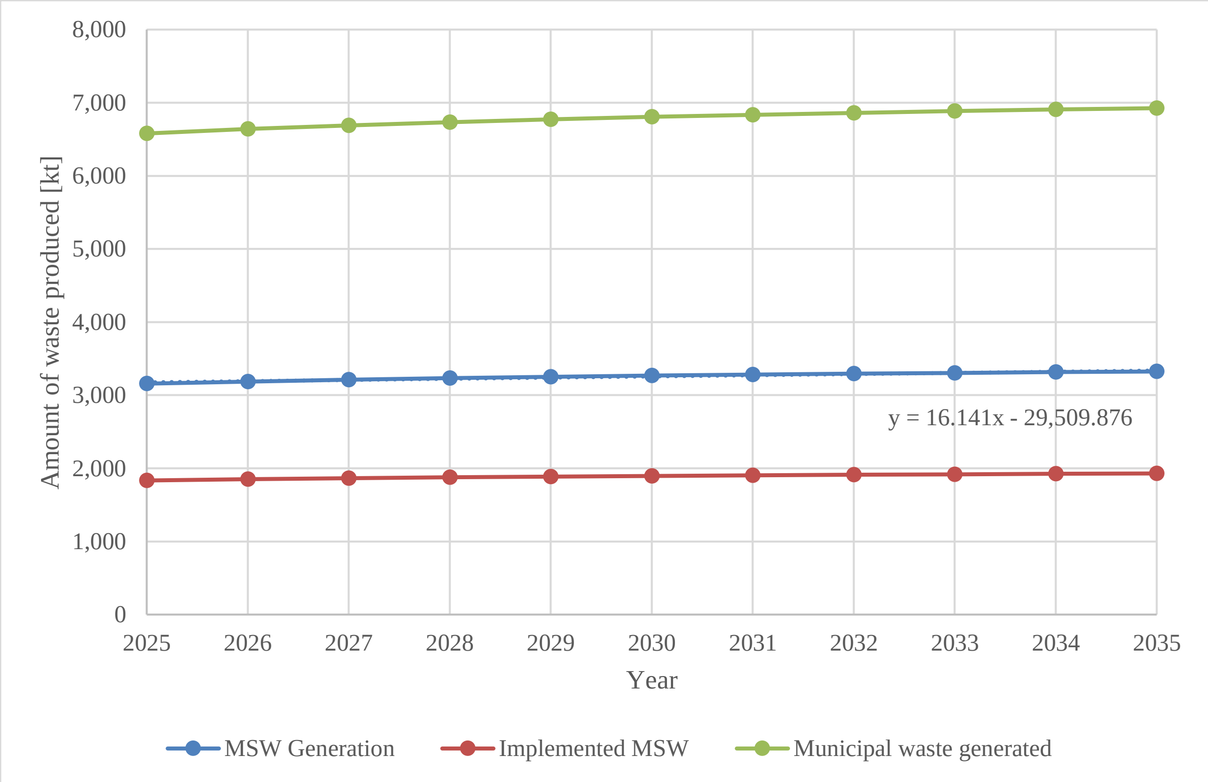

Figure 8-1 Prediction comparison of MSW generation to 2035

Figure 8-1 compares the prediction of the generation of municipal solid waste based on the predictive model from the website application TiramisO of the TIRSMZP719 project with the model that includes the implementation of municipal solid waste presented in the case study.

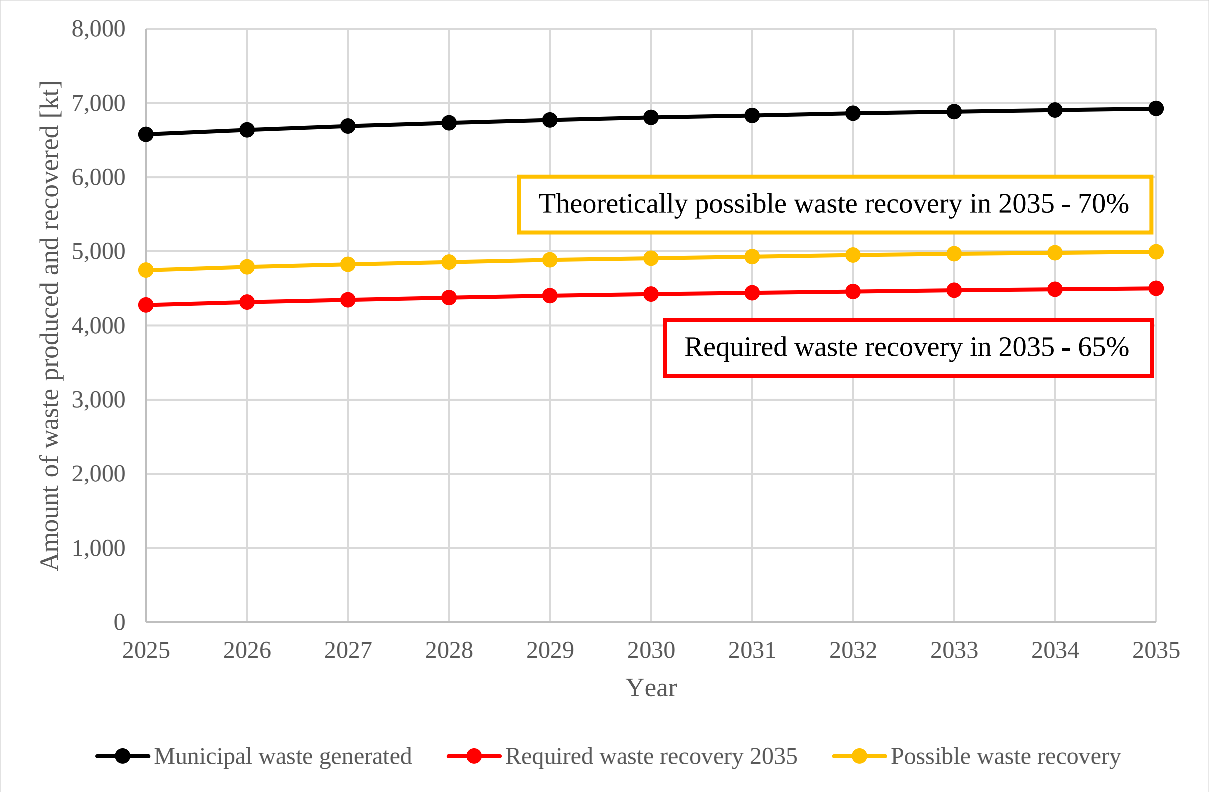

Figure 8-2 Comparison of required and possible waste recovery

As Figure 8-2 shows, the suggested implementation would increase the value of recovered waste to about 70% of the total municipal waste generated, so it is theoretically possible, with sufficient effort, to achieve the required amount of 65% recovered waste in 2035 required by the Czech Republic's waste management goals, according to Annex No. 1 to Act No. 541/2020 Coll. The value of approximately 70% of the possible waste recovery can be achieved with the theoretical implementations presented in the case study for paper, plastic and biodegradable waste streams, which theoretically should be fully recovered from municipal solid waste.

The master thesis can be described as a successful one. The aims of the thesis were fulfilled, and the thesis presents a useful tool for waste management. The master thesis presents possible applications of the tool as well as automates and optimizes the process of obtaining the results. The master thesis demonstrated the applicability of the waste composition analysis tool in supporting sustainable development and is useful for the promotion and achievement of the circular economy.

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LIST OF ABBREVIATIONS

MSW	Municipal solid waste
SWA	Solid waste analysis
MW	Municipal waste
VBA	Visual Basic for Application
TIRSMZP719	Prognosis of waste production and determination of the composition of municipal waste
PET	Visual Basic for Application
Biowaste	Biodegradable waste