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In order to decrease environmental impacts in waste management the choice of treatment method must be based on the characteristics of the waste. Present sampling procedures do not provide statistically representative samples of solid waste and this provides difficulties in characterization. The objective of this study was to develop a procedure for waste component analysis and sampling of waste after collection and at plant level. A further objective was to characterize the waste delivered to an incineration plant for physical and chemical properties and to determine the amounts of delivered waste that could be classified as biofuels and fossil fuels. The proportions of recyclables and hazardous waste were also examined. Samples were taken randomly from waste trucks and divided by square implementation. Statistical analysis of the results showed that the number of sub-samples could be decreased with only a moderate increase in the confidence interval. This means that future waste composition analyses could be made more efficient and thereby less expensive. The analysis of the waste delivered to the Lidköping incineration plant (Central Sweden) showed that 66.4% of the household waste was composed of biofuels and 21.3% of non-renewable combustibles, of which 40.3% were recyclables. In addition, 11.6% of the household waste was non-combustible and 0.6% hazardous waste. The heat value for the biofuels was 18.0–19.7 MJ kg^{-1} dry mass (DM) and for the fossil fuels 28.2–33.9 MJ kg^{-1} DM. The industrial waste consisted of 35.9% biofuels, 62.0% fossil fuels, 1.6% non-combustible and 0.5% hazardous waste. The heat value was 19.5 MJ kg^{-1} DM for the biofuels and 31.4 MJ kg^{-1} DM for the fossil fuels.

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Introduction

In choosing an appropriate treatment method for individual parts of a waste stream it is important to understand the characteristics of the waste, reflecting consumption patterns and lifestyle as they vary between different regions. National accounts of waste can therefore not be used to characterize waste in a particular region. Furthermore, the national accounts do not reflect the characteristics or treatability, but rather the opinion of those responsible for management (e.g. Naturvårdsverket 2004). The characteristics of the waste also change with time and therefore it is important to monitor the conditions on a regular basis. Recent data on the waste stream are unavailable and outdated standard values or comparisons with other municipalities are often used. Many of the analyses that have been carried out in Sweden have been sampled at source, namely the household, a method that requires relatively extensive record-keeping and extra staff. In other cases large amounts of waste (whole truck loads) have been analysed. This results in a large workload that does not necessarily correspond to a higher reliability in results. Small samples (e.g. 100 kg) yield equally valid results on the composition of a given supply of solid waste as a large sample of up to 800 kg would do (Klee & Carruth 1970). Statistical analyses have not been a major part of waste component analyses (conducted in Sweden), and the problem is still to find a way to obtain a representative sample.

The Swedish government is now proposing a requirement on incineration plants to characterize all waste delivered through waste component analysis (Miljödepartementet 2003). The heterogeneity and extent of the waste flow makes it important to develop a method for sampling that will yield representative samples. As this can be resource-demanding and unpleasant work, it is essential to identify and use efficient sampling methods.

This study presents results and a statistical analysis of the methodology used for a waste composition analysis of household waste delivered to the Lidköping incineration plant, conducted in October and November 2003. The main objective was to develop a method for sampling and characterization of household waste for its physical and chemical features. A further objective was to evaluate the composition and characteristics of the waste delivered to the incineration plant in Lidköping and to determine the share of biowaste and fossil fuels and the heating value of these fractions, the proportion classified as hazardous waste under the new legislation and the proportion that falls under producer responsibility.

Background for the Lidköping case study

Incineration is the most common treatment method for household waste in Sweden: 38.3% of household waste is incinerated. The environmental effects of waste incineration depend on the characteristics of the waste and the efficiency of the incineration and stack gas cleaning processes.

The incineration plant in Lidköping – Lidköpings Värmeverk AB (LVV), owned by the municipality – was put into operation in 1986. Waste is brought from Lidköping and 15 other nearby municipalities. The incineration plant runs continuously all year around, with a short intermission for maintenance during the summer. Every year, approximately 50 000 tonnes household waste and 20 000 tonnes industry/production waste are delivered to the plant.

The energy from the incineration provides district heating for 90% of the residences and approximately 65% of the industries in the municipal centre. In 2001, a total of 170 GW h were generated from waste incineration. LVV also has a 4 MW turbine that generated 20 GW h of electricity in 2001 (Lidköping 2003). Approximately 250 tonnes of waste is incinerated daily during winter when the demand for district heating is high, down to 50 tonnes during summer when the demand decreases.

The plant's permit states that it may only burn non-hazardous waste. As Sweden incorporated new EU legislation in 2003, a number of fractions have been reclassified as hazardous waste, although at the moment LVV has a dispensation to burn reclassified fractions that were included in their permit. The condition for this dispensation is that LVV reports the fractions and amounts concerned.

Another important factor for the company is how waste is classified as a fuel. Fossil fuels used for generation of electricity are currently subject to taxation. To avoid all fuel being classified as fossil fuel, LVV has obtained an injunction allowing it to report to the County Administrative Board (CAB) how much of the waste consists of fossil/non-renewable material and how much can be classified as renewable fuel.

To fulfil these demands, LVV decided to carry out a classification and evaluation of the incoming waste and commissioned AnalyCen Nordic AB and Dalarna University College to carry out the study. Dalarna University College was responsible for the design and testing of the methodology for waste component analysis and AnalyCen Nordic AB was responsible for the chemical characterization of the waste.

Materials and methods

Samples were taken at the incineration plant; each sampling unit consisting of one truckload. Waste delivered at night and during weekends came from transfer stations in neighbouring municipalities that also delivered during weekdays, and there was no reason to believe it to be different from the daytime waste. Samples of household waste were taken on five weekdays between 0800 and 1700 h: Tuesday and Thursday in week 43 and Monday, Wednesday and Friday in week 44. Between those hours a minimum of 16 trucks arrive every day and five of these were selected randomly.

The selected trucks were redirected to an empty hall. The waste was unloaded onto a tarmac surface and arranged into a rectangular shape using a front-end loader. The rectangle was divided into 4×5 squares and sub-samples were taken from the middle of 10 randomly chosen squares. The sub-samples were demarcated using a 0.5 m × 0.5 m wooden frame and stored in plastic sacks.

The weight of each sub-sample was recorded on a Mettler DTL 60J-scale with a maximum capacity of 60 ± 0.02 kg. The content of a sack was sorted into three main categories (biofuels, fossil fuels and non-combustibles), which were further divided into 12 sub-categories (see Table 3). After five sub-samples were sorted, the clean fractions were weighed and totalled and the remaining five sacks sorted in the same way.

Statistical analysis

The results for the household waste composition were analysed to evaluate their reliability for planning similar studies in the future.

In preliminary studies it was found that the sampling day did not significantly influence the variables M_{HW} ($P = 0.09$) or M_{NC} ($P = 0.56$); that is, there was no significant daily variation during the study period.

To perform the statistical analysis, the household waste was divided into three groups: hazardous waste (HW), non-combustibles (NC) and combustibles (bio- and fossil fuel waste, C). The proportions of non-combustibles and hazardous waste were chosen to be included in the statistical analysis since they represent the smallest proportion of the waste flow and are therefore the most difficult to accurately predict. In addition, these constituents limit the efficiency of the incineration process and can therefore be important targets for future information campaigns. To obtain an estimate of the proportion of non-combustible (P_{NC}), the GLM procedure in the SAS/STAT package (SAS 1999) was used to model the mass of non-combustibles in a sample (M_{NC}) as a general linear model

$$M_{NC} = P_{NC}\,M + e \qquad (1)$$

where M_{NC} = mass of non-combustible in a sorting sample; P_{NC} = proportion of non-combustibles; M = total mass of the sorting sample; e = error term. No intercept was included in the model.

Similarly, an estimate of the proportion of hazardous waste (P_{HW}) was sought using a corresponding model for the mass of hazardous waste in a sample (M_{HW}). M_{HW} showed non-normal distribution of residuals. Therefore, the GENMOD procedure in the SAS/STAT package (SAS 1999) was used to model M_{HW} as a generalized linear model (McCullagh & Nelder 1989) with a log-link function, a gamma distribution and with fixed offset value; that is, not a predictor variable, equal to log(M)

$$\log(M_{HW}) = \text{offset} + \alpha + e \qquad (2)$$

where M_{HW} = mass of hazardous waste in a sorting sample; α = constant, an estimate of $\exp(P_{HW})$.

Model (1) had a high goodness-of-fit ($R^2 = 0.93$) and model (2) also fitted the data well (scaled deviance = 27.5 with 24 degrees of freedom).

It was assumed that the period chosen was representative for the year and that the estimates of P_{NC} and P_{HW} give adequate estimates of the proportion of non-combustibles and hazardous waste arriving at the incineration plant per year.

Chemical analysis

For chemical analysis of household waste, two laboratory samples of each of the following composite groups were prepared

- biowaste
- biofuel under producer responsibility (paper and paper packaging)
- other biofuels
- fossil fuel under producer responsibility (plastic packaging)
- other fossil fuels.

Biowaste was analysed separately due to its characteristics. At the end of the day the sorted biowaste was divided, by coning and quartering (Nordtest 1995), until approximately 1% (approx 5 L) of the total biowaste sorted that day remained. This laboratory sub-sample was stored in a freezer. Stored biowaste samples from 1 week were later mixed and dried, and then passed through a Retch-mill before chemical analysis.

The other fractions were stored for 1 week and later divided by cone and quartering until approximately 20 L remained. The laboratory sample was crushed in a hammer mill to an approximate grain size of 10 cm before chemical analysis.

Samples of industrial waste were taken on five consecutive weekdays, 3–7 November, between 0800 and 1700 h. On the first day all waste was set aside, mixed and divided at the end of the day. As this left too little waste for incineration, on the following days each load was directly divided into two piles, of which one was saved. At the end of each day the sample was mixed and divided into two piles, and this was repeated five times until approximately 8% of the initial weight remained. The sub-samples were stored and hand-sorted as one sample in the following week. The sorted waste was stored in containers; the combustible fractions were weighed on the weighing scales at the incineration plant (± 20 kg) and the non-combustible and hazardous waste on the Mettler scales used for household waste. In the evaluation of industrial waste only four categories were used: biofuels, fossil fuels, non-combustible and hazardous waste.

The laboratory samples were sent to an accredited laboratory for analysis. Each sample was ground, dried overnight at 105 °C, and analysed for the content of dry matter (SS

Table 1: Total waste in samples and weight sorted.

Day	Waste in sampled trucks (tonnes)	Sorted samples (kg)	Sorted samples (% of day sample)
1	26.7	750	2.8
2	32.7	729	2.2
3	29.2	688	2.4
4	32.7	764	2.3
5	35.4	665	1.9
Total	165.7	3595	2.3

1878170), ash (SS 1878171) and energy on wet and dry basis (SS-ISO 1928).

Results and discussion

Household waste – method evaluation and composition

Household waste from 5 days was analysed, with five samples from each day. In total the waste in the sampled trucks had a weight of 165.7 tonnes, whereof 3565 kg or 2.3% was sorted (Table 1). The individually sorted samples weighed 90–189 kg, which, according to Liu *et al.* (1997). is the optimal sample size considering both accuracy in results and workload.

The proportion of non-combustibles was estimated to be 0.116 (Table 2) with a standard error of 0.67%. The proportion of hazardous waste was estimated to be 0.0063 (Table 2). As model (2) is not linear there is no estimated standard deviation for the estimated proportion of hazardous waste. However, the uncertainty of the estimate is shown by the confidence interval in Table 2. The narrow confidence intervals obtained for these fractions demonstrate that the method used provides a relatively accurate estimate of proportions. Non-combustibles and hazardous waste are the smallest fractions of the waste flow delivered to LVV, and these fractions also tend to have an uneven generation rate in households. It is therefore reasonable to assume that the method also gives a good prediction of the other major components in the waste flow.

On average for all days, on a wet weight basis 66.4% of the waste was biofuels, 21.3% fossil fuels, 11.6% non-combustibles and 0.6% hazardous waste (Table 3). Of the waste evaluated, 40.3% was recyclables, of which 4.6% was non-combustible recyclables. An additional 33.0% was biowaste, that is, material that can be composted or anaerobically digested. The relative proportions of the measured fractions are presented in Table 3. Based on its characteristics, 73.3% of the household waste alone was suitable for material recycling (including 4.6% non-combustibles) or biological treatment.

Table 2: The 95% confidence interval for the proportion of non-combustibles and hazardous waste using ten sub-samples.

	Estimate	Lower	Upper
P_{NC}[a]	0.116	0.103	0.130
P_{HW}[b]	0.0063	0.0048	0.0083

[a]Estimate from model (1). [b]Estimate from model (2).

Table 3: Composition of household waste delivered to Lidköping incineration plant (wet weight).

Fraction	Weight in evaluated sample (kg)	(%)
Bio-fuels		
Biowaste	1177	33.0
Paper/newsprint	503	14.1
Paper packaging	352	9.9
Other bio-fuels	334	9.4
Total	2366	66.4
Fossil fuels		
Hard plastic packaging	111	3.1
Soft plastic packaging	306	8.6
Diapers	232	6.5
Other fossil fuel	112	3.1
Total	761	21.3
Non-combustibles		
Glass packaging	86	2.4
Metal packaging	80	2.2
Other non-combustible	250	7.0
Total	416	11.6
Hazardous waste	23	0.6

The obtained results for the waste composition are comparable with those found in other Swedish studies of household waste, where values of 28.3–50.4% biowaste, 17.8–30.6% combustibles, 3.7–13.2% inert non-recyclables, 7.8–25.0% paper and paper packaging, 2.1–15.2% plastic packaging, 1.5–4.4% glass packaging and 1.3–7.1% metal packaging have been reported (Olsson & Retzner 1998, Mattsson & Berg 2000a,b, Lundbäck 2000, Vikicevic et al. 2001). Those studies were carried out on household waste in sacks and bins (bagged waste), whereas the present study was carried out on waste delivered to the incineration plant, namely municipal solid waste (MSW). The relatively high content of paper and cardboard and low biowaste content indicates that waste from offices and other businesses were part of the samples.

In all, 23 kg of hazardous waste was found in the sorting samples. It consisted mainly of electrical goods (43.4%), electric wires (17.5%), small batteries (8.8%) and spray cans (6.6%). The first two fractions have recently been reclassified as hazardous. It should also be noted that all material connected to hazardous waste, for example, a lamp base with electric wires, was sorted as hazardous waste.

The composition of the household waste delivered to LVV can also be compared with how household waste is treated in

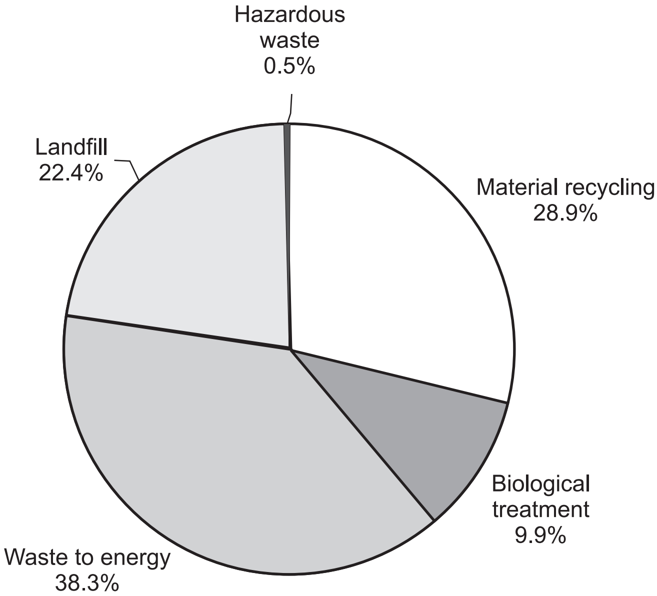

Fig. 1: Treatment of household waste, Sweden 2002 (RVF 2003)

Sweden today (Figure. 1). As regards waste characteristics, this comparison indicates that there is a potential to increase the recovery rate and thereby decrease the quantities of waste to be sent to landfills. However, in reality there might be a lack of treatment capacity as the landfill bans on receiving combustible and organic waste are implemented (Sundberg 2000). Treatment capacity, collection systems and the market for recycled material must improve before actual waste minimization can occur.

Industrial waste

In total 3380 kg of industrial waste were evaluated and found to consist of 62.0% biofuels, 35.9% fossil fuels and 1.6% non-combustible (Table 4). In the industrial waste, the share of hazardous waste was low, 0.5% (Table 4). The hazardous waste found (17.36 kg) consisted of mainly electrical waste (51.4%), electric wires (21.9%), paints and oils (10.4%) and glue and sealants (8.1%).

Moisture and heat value

The inflow to the incineration plant is composed of household waste and industrial waste. The calculation of average composition of the waste delivered to LVV (Table 4) was based on the information that 50 000 of the 70 000 tonnes delivered are household waste and the rest industrial waste.

In the household waste the water content varied widely between fractions (17.9–67.5%) (Table 5). The heat value for the biofuels was 18.0–19.7 MJ kg^{-1} dry mass (DM) and for the fossil fuels between 28.2 and 33.9 MJ kg^{-1} DM (Table 5). Based on the composition in Table 4, the heat value of the mixed wet household waste was 10.8 MJ kg^{-1}.

The industrial waste had a water content of 11.0–25.6% and the heat value was 19.5 MJ kg^{-1} DM for the biofuel and 31.4 MJ kg^{-1} DM for the fossil fuel (Table 5). The heat value of the wet mixed industrial waste was 19.0 MJ kg^{-1}.

It can be seen that the major weight proportion (65.2%) of the waste can be classified as biofuels (Table 4). However, as the heat value is lower for the biofuels, the major proportion

Table 4: Composition of delivered waste (%).

Fraction	Household waste	Industrial waste	Total
Biofuels	66.4	62.0	65.2
Fossil fuels	21.3	35.7	25.5
Non-combustibles	11.6	1.6	8.7
Hazardous waste	0.6	0.5	0.6

Table 5: Water and ash content, and heat value in waste as delivered to LVV, and the share of total energy generated from each fraction.

	Water	Ash	Heat value		Share of total energy[a]
Fraction	(%)	(%)	(MJ kg^{-1} wet)	(MJ kg^{-1} DM)	(%)
Household waste					
Biowaste	67.5	17.2	6.1	18.8	10.9
Recyclable biofuels	26.9	12.6	13.2	18.0	17.1
Other biofuels	38.7	11.4	12.1	19.7	6.1
Fossil recyclables	43.9	10.0	19.1	33.9	12.0
Other fossil fuels	17.9	16.7	23.2	28.2	12.1
Industrial waste					
Biofuels	25.8	10.5	14.5	19.5	19.8
Fossil fuels	11.0	9.1	28.0	31.4	22.1

[a]Of all wet waste delivered.

Table 6: The 95% confidence intervals for the proportion of non-combustibles and hazardous waste using five sub-samples.

	Estimate	Lower	Upper
P_{NC}	0.113	0.094	0.131
P_{HW}	0.0063	0.0043	0.0092

of the energy is generated from fossil fuels (Table 5). The average heat value of the waste stream, consisting of 71% household waste and 29% industrial waste (as wet weight), was estimated at 13.3 MJ kg^{-1}. Even though around 66% of the incinerated material was categorized as biofuel, due to the low energy content and high water content in the biofuels, especially biowaste, almost half the energy generated in direct combustion came from fossil fuel (46.2%).

Statistical analysis for planning future studies

An additional statistical analysis of the proportions P_{NC} and P_{HW} was performed to investigate the influence of the number of sub-samples on the confidence intervals of these proportions. Including only five sub-samples from each truck instead of ten increased the 95% confidence intervals by 40% for P_{NC} and P_{HW}, using models (1) and (2) (Table 6). In future waste component analyses, it would be possible to generate reliable results from fewer sub-samples per truck, hence decreasing the workload and the costs connected with the analysis.

Conclusions

The analysis of the results of this study show that sampling at plant level using square implementation gives reliable predictions of the composition of the delivered waste. The statistical analysis further shows that the number of sub-samples could be decreased in the future, thereby decreasing the workload and costs connected with the waste component analysis. However, the number of sub-samples cannot be reduced to the extent that the total sorting sample is less than 90–140 kg (Liu & Lipták 2000).

The sorting categories in this initial testing of the method were chosen to correspond with those required by the CAB in the LVV annual report, but can in the future be adapted to the needs of a specific region.

Incineration with heat recovery can divert waste from landfills and is considered by many to form part of sustainable waste management. This study showed that more than two-thirds, by weight, of the waste delivered to the incineration plant in Lidköping consists of material classified as biofuels. However, due to the relatively high energy value and low water content in the one-third of the waste classified as fossil fuels, this generates almost 50% of the energy from direct incineration.

It is possible that landfill taxes will increase in the future, thereby providing a stronger financial incentive for landfill diversion. On the other hand there are discussions in Sweden on introducing taxes on incineration and there will also most probably be a lack of treatment capacity as the landfill bans on receiving combustible and organic waste are implemented. It is therefore important to incinerate the 'right' kind of waste. Based on its characteristics, 73.4% of household waste could be suitable for material recycling or biological treatment. As regards energy and water content, the chemical analysis in this study indicates that industrial waste is more suitable for energy recovery than household waste. This will become more interesting as there will probably be a lack of incineration capacity in Sweden in the near future (Sundberg 2000, Miljödepartementet 2003).

The low share of hazardous waste (0.6%) indicates that information programmes concerning this fraction have had some success. As most of the hazardous waste found belonged to fractions that recently have been reclassified as hazardous, there is a good chance that the amounts of these can be decreased even further as the new information disseminates.

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