Evaluation of different pretreatment systems for the energy recovery of greenhouse agricultural wastes in a cement plant

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Abstract

This work evaluates and selects the best sequence of operations for the pretreatment of greenhouse agricultural wastes (GAW) derived from the main greenhouse crops of the west of Almeria (Spain), such as tomatoes, peppers, cucumbers, eggplants, zucchinis, watermelons and melons, before recovering its potential energy in a cement plant located in this province. In this research, a set of operations are proposed to reduce the chlorine percentage and the moisture content presented in this kind of waste, for its use as an alternative fuel in this production facilities. A washing of the waste under optimal conditions may reduce the chlorine content by approximately 50.0% of the original value and increase the lower calorific value by 8.0%. Drying the waste with a hot gas stream could produce a recoverable waste with a moisture content lower than 3.0%, which enables its temporary storage while avoiding its degradation. The use of an adequate amount of conditioned GAW can provide a substitute up to 51% of the conventional fossil fuel currently employed in the daily operation of the facility evaluated, leading to a reduction of the CO_2 emissions associated with the decrease in the fossil fuel consumption.

Keywords

Waste to energy; Biomass waste; Alternative fuels; Waste management; Biofuel; Rotatory kiln; Greenhouse wastes.

Introduction

Agricultural waste management is essential to avoid the increasing environmental problems in those areas where the primary sector is the main economic resource of the region [1]. For example, 90% of agricultural wastes produced in Andalucía (Spain) come from agricultural sector and remainder are from animal production [2].

By 2050, the projected growth of the world population together with the need to increase food production [3], makes that agricultural waste may be considered an untapped biomass resource whose improvement management is required to move forwards towards a low carbon circular economy [4].

Nowadays, agricultural waste may be turned into suitable products, such a fertilizer, energy and other materials, using different conversion process. However, the processed of agricultural waste is difficult due to their heterogeneity and their seasonal nature, especially if they come from the intensive agriculture activity such as wastes evaluated in this work, whose production volume and type of crops vary over a year [5]. Anaerobic digestion process is one of the most mature technology employed to convert many agricultural waste into a biogas and fertilizer [6]. However, this conversion technology presents some weakness in terms of the quality of biogas generated and the development of a save agriculture that reuse the anaerobic digestate produced as renewable fertiliser [7].

Production of bio-products, such a chemicals or polymers [8], or biomaterials, such as innovate building blocks [9], are increasingly widespread. Nevertheless, there are some technological elements, for example the energy consumption employed, the variability in chemical composition of the waste feedstocks or the social perception, that limit these developments [1].

Energy production from agricultural waste is also a common practice in countries like Sweden, Denmark, Netherlands, USA, Canada, Austria and Finland. “Waste - to – energy” conversion processes for electricity or heat production may have an economic and market potential, if the processing technology is conveniently selected considering the nature and the structure of the biomass feedstocks, and seeing the objective sought [10]. There are different thermal methods to convert the agricultural waste in energy. The most employed are combustion, gasification and pyrolysis process.

For the industry sector, combustion is the most extended thermal conversion technology for the generation of thermal power. In particular, the co-firing or co-combustion of wastes with a fossil fuels or other alternative fuels may provide some advantages over conventional combustion, for example, low risk and low cost for renewable energy generation avoiding the construction of new dedicated biomass power plant [11], [12].

Cement industry is considered an energy-intensive industry and is one of the major anthropogenic sources of greenhouse gas emissions (30% of the total CO_2 emissions in the world) [13]. Eighty percent of its energy consumption corresponds to the thermal energy required to produce clinker, which is the base product for the manufacture of cement. This consumption is located in the main burner of the rotatory kiln, and the later is often provided by fossil fuel such as pet coke, together with the pre-processing alternative fuels such as used tires, sawdust, residual solvents and other wastes [14]. The robust operational conditions of these installations allow the energy recovery by co-combustion of a large variety of wastes under the compliance requirements demanded for the use of new alternative fuels [15]. In particular, the chlorine content, the lower calorific value (LCV) and the moisture content should be within the limits established in the so-called Integrated Environmental Authorisation (IEA), which is specified for each installation.

In 2017, the total substitution percentage of fossil fuel in the Spanish cement plants was 26.6%, which is below 44.4%, the average percentage established for the European Union [16]. The 88% of the cement plants in Spain are authorized to use refuse - derived fuels (RDF), among which are biomass or wastes derived of the agricultural activities [17]. However, a knowledge gap has been found in the use of agricultural wastes as evaluated in this work, as an alternative fuel in cement plants or in another type of industry.

Agricultural wastes analysed in this work, hereinafter called greenhouse agricultural wastes or GAW, come from the intensive agriculture of greenhouse of the west of Almeria (Spain). They are picked up at the end of the harvest and, most of them, taken to an authorized waste treatment plant located in El Ejido (Almeria), where they are accumulated and transformed into vegetable compost.

The increase in crop production in the last years means that around 1.2 million tons of GAW per year are generated in the region [18]. The growing accumulation in the environment and in waste treatment plants, make necessary the development of alternative solutions to composting or the production animal feed, which are management methods currently used.

In this sense, and in view of the interest showed by a cement plant located in Almeria for co-combustion these wastes in the rotatory kiln, it is proposed the evaluation of different pretreatment systems to obtain an adequate fuel that made it possible to reduce the current level consumption of fossil fuel in the cement plant.

Experimental section

To obtain an adequate fuel for the cement plant from GAW, it is important to know the properties of them and the requirements of the installation to ensure a sustainable burning of these wastes. In this case, the cement plant is in the province of Almeria (Spain), close to the waste treatment plant where GAW were collected.

The requirements are showed in the specific IEA of the cement plant. In this document are defined the acceptable limits of those parameters that ensure an efficient combustion of alternative fuel in this process, considering the technical characteristics of the installation. These parameters, called as key parameters, are mainly the chlorine content (Cl), the sulphur content (S), the moisture content (W) and the low calorific value (LCV).

Once the key parameter limits are known, it is necessary to analyse the physico-chemical properties of the GAW collected in the waste treatment plant. These wastes consist of a mixture of stems, leaves and unsuitable vegetables for sale derived from the main greenhouse crops of the west of Almeria, such as tomatoes, peppers, cucumbers, eggplants, zucchinis, watermelons and melons.

A total of eight GAW samples were received at the fuel testing laboratory of the School of Engineering of Seville (ETSI) during year. The GAW samples were collected in the waste treatment plant located in Almeria, following a sampling method specifically designed to ensure collected representative samples from waste heaps stored on this facility (figure 1). The GAW sampling method was planned according to UNE-EN 14899:2007 [19].

Figure 1. Waste heaps for GAW sampling on waste treatment plant.

Each GAW sample was forwarded to the ETSI laboratory. The chlorine content (Cl), the sulphur content (S), the moisture content (W), the ash content (Ash) and the LCV were measured on each sample according to Solid Biofuels Standards.

To determine the chlorine content was used a potentiometric titration in accordance with UNE-EN ISO 16994:2015 [20]. The sulphur content was determined using a LECO® elemental analyser.

The moisture content and the ash content were determined by thermogravimetric methods. For it was considered the UNE-EN 18134-2:2016 [21] and UNE-EN 18134-3:2016 Standards [22] and UNE-EN ISO 18122:2016 Standard [23], respectively.

The measured of the LCV was carried out using a bomb calorimeter following the criteria described in the UNE-EN 18125:2018 Standard [24].

Figure 2 and figure 3 show the values measured in the laboratory on the eight GAW samples evaluated in this work.

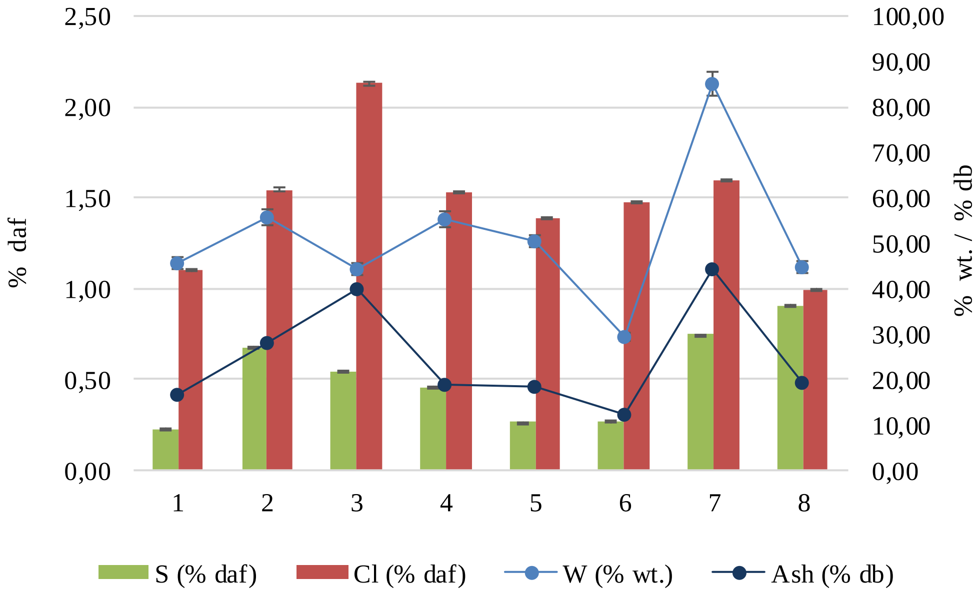

Figure 2. Chlorine content and sulphur content in wt. % dry ash-free base (% daf), ash content in wt. % dry base (% db), and moisture content in wt. % (% wt) of GAW samples received in the ETSI laboratory.

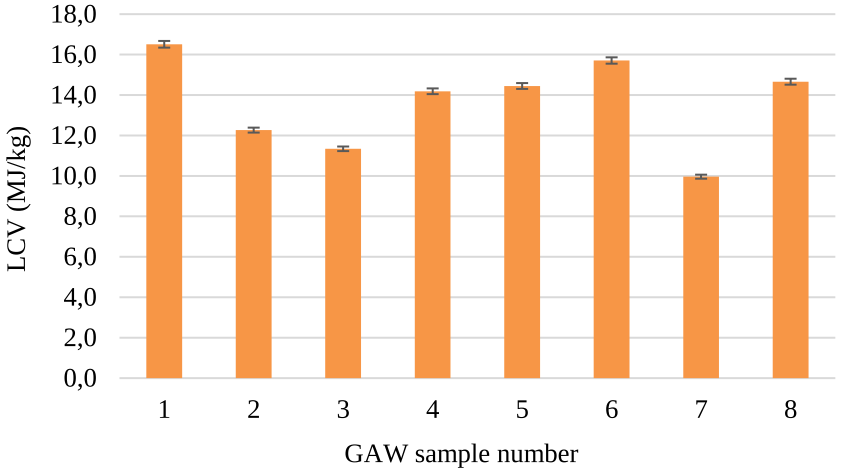

Figure 3. Lower calorific value expressed in MJ/kg dry base of GAW samples received in the ETSI laboratory.

Chlorine, sulphur and ash content were measured on each GAW sample at least 4 times. The error analysis associated of each measured was lower than 0.4%, 0.5% and 0.5%, respectively. Moisture content was determined by successive oven-drying and weighing operations of each sample. Moisture value was defined when the difference between two consecutive weights was less than 3%. LCV was established when the difference between two measured in the same sample was less than 150 kJ/kg.

The chlorine content varied between 1.0% and 2.0%, the sulphur content between 0.2% and 0.9%, the ash content between 16.8% and 44.0%, the moisture content between 29.0% and 85.0% and the LCV between 10,000 kJ/kg and 16,000 kJ/kg. These variations could be associated, on the one hand, with the seasonal nature of GAW since different crops are planted along a year and, on the other hand, with the harvesting methods employed in the greenhouses. At the end of the harvest, each farmer clears his cultivation area for the next crop, removing all wastes generated (stems, leaves, unsuitable vegetables for sale, small stones and soils) without following any selective collection plan. These wastes are transported to an authorised waste treatment plant. In this work, the waste treatment plant where the GAW were collected receive much of the wastes generated in the greenhouses of the west of Almeria.

However, despite these variations, only the chlorine content and the moisture content does not complain with the limit values defined for using these wastes as an alternative fuel in the cement plant ($Cl_{AFR} < 0.8\%$ and $W_{AFR} < 8.0\%$).

The average LCV associated to the GAW was 13,600 kJ/kg. This value is similar to LCV associated with other familiar waste, such as cereal straw (13,200 kcal/kg), branch of the vine (13,700 kJ/kg) or grape marc (13,540 kJ/kg).

After analysing the values of these parameters in each sample of waste, a list of pretreatment system of GAW was defined. The conditioning operations of each sequence of operations were established comparing the results achieved in each parameter measured in the laboratory with the limit values defined in the IEA of the cement plant.

Once the pretreatment systems list was defined, each of the eight GAW samples received in the laboratory was tested following each sequence of operations showed in the list. A pretreated GAW sample was obtained from each sequence of operations tested at the laboratory. The level of chlorine, sulphur, moisture, ash and LCV in these pretreatment samples were measured. For each pretreatment systems tested, an average value of each key parameters was estimated and compared with its average value measured on the GAW samples received in the laboratory, that is, on the GAW without pretreatment. The average values associated to the GAW without pretreatment were considering as reference values to analyse the efficiency of the pretreatment system tested at the laboratory.

The sequence of operations that provided a higher quality of GAW with the lowest resource consumption, such as solvents or energy for conditioning of the wastes, was finally selected as the best pretreatment system to generate an alternative fuel (AFR) for using in the cement plant.

Figure 4 shows the procedure followed from the reception of GAW samples in the ETSI laboratory, to selection of the best sequence of operations to convert the GAW into a suitable AFR.

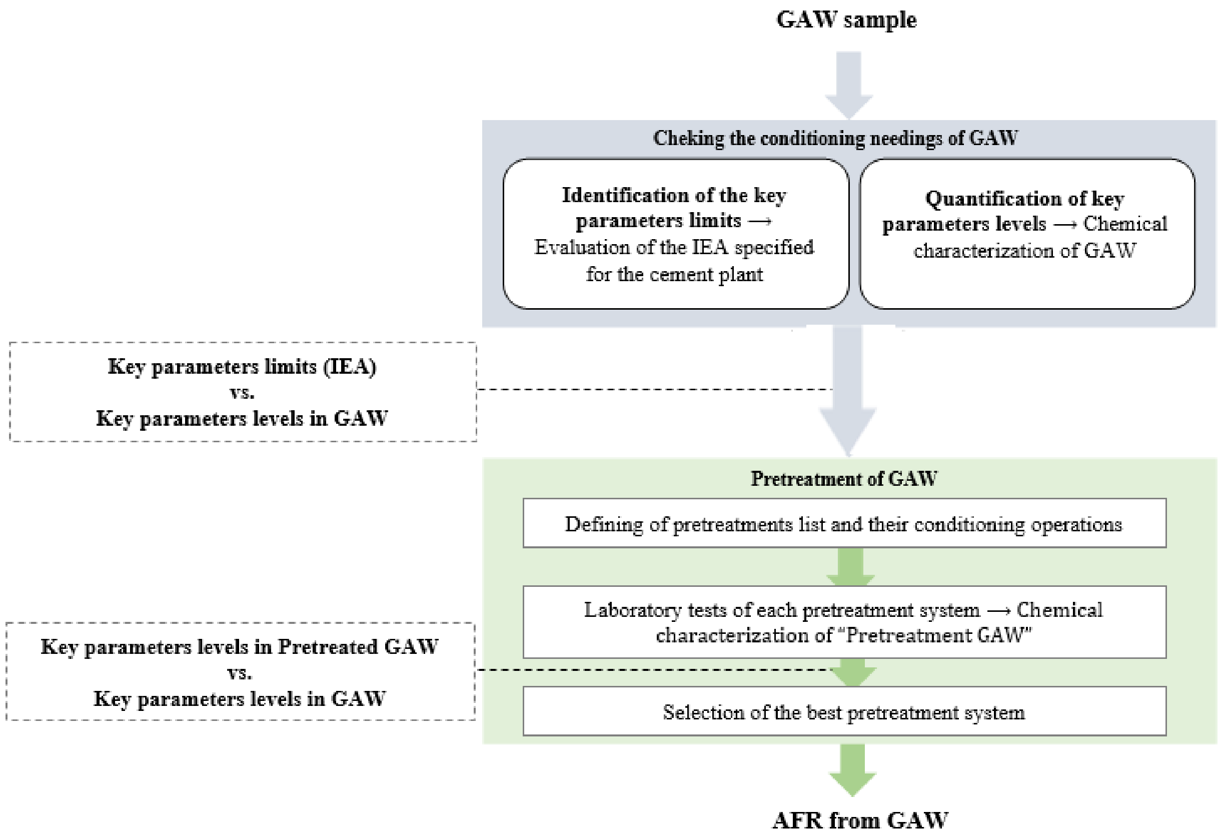

Figure 4. Procedure followed to select the best GAW pretreatment system to generate an alternative fuel for a cement plant.

To define the sequence of operations and the operative conditions that constitute each pretreatment systems tested at the laboratory, the attention was paid in the chlorine content and the moisture content present in the GAW samples received in the ETSI facilities. On the one hand, the chlorine is considered a “poison” for the cement plants because it causes technical problems in the process [25] and, on the other hand, the moisture content in a fuel reduces the energy potential of the waste.

If the chlorine contained in the GAW is higher than the limit defined in the IEA, a washing (W) of the GAW should be considered. For it, this operation was optimized looking the minimal operational cost, which involve a minimal of wash solvent consumed per kilogram of wash waste ($R_{Opt.}$), a minimal residential time ($t_{Opt.}$) and a minimal temperature at which the wash solvent ($T_{Opt.}$) was used. For the evaluation of the washing operation, an on-site control of the chlorine content in the wash solvent was used along, together with a subsequent quantification of this parameter on the pretreated GAW sample.

If the moisture content is too high, the most economical operations that would allow minimizing this value, such as drying with hot air, should be considered (D). The temperature was estimated in a specific laboratory test, including as well if needed pressing of the waste (P).

In addition, a triage (Tg), milling (M) and screening (Sc) were considered necessary to remove the solid impurities contained in the GAW and reduce the particle size. The latter is an essential parameter ensuring an efficient feed through the kiln burner (≤ 10 mm). The triage and milling operations were carried out in the waste treatment plant where GAW samples were collected. Screening, washing, pressing and drying operations were implemented in the ETSI laboratory.

The screening was developed by hand. For it, each GAW sample was extended in a table to facilitate the elimination of the impurities such as small stones, pieces of plastic, still wires, among other things.

The washing of the GAW samples was carried out by hand using a plastic container. Thus, a waste sample was introduced into the recipient, together with a certain volume of solvent and at a set temperature and washing time.

The drying of the waste was tested at the laboratory, using a custom system developed especially for this work (Figure 5). It consisted of a wooden crate with a porous bottom, which circulates a flow of hot air coming from a heater ($T_{\text{Hot air) maximum}}$ = 85 ºC). This flow crosses the layer of wet GAW sample that was previously deposited on the porous bottom. The hot air allowed to dry the waste samples up to moisture values lower than 2.5% in a short period of time.

Figure 5. Drying of GAW sample in ETSI laboratory. Details of custom system developed for this work.

Before conducting the drying test, the ignition temperature of GAW was measured. This parameter was determined to ensure that the temperature of hot air used for drying of wastes was lower than this value. The ignition temperature of GAW was tested at a laboratory test. For it, the temperature of five GAW sample was continuously monitored using a thermocouple connected to a data acquisition system. The analysis of the data collected during the test enabled the identification of the ignition temperature associated with the GAW (Figure 6). In this way, the temperature of the flow of hot air should be consistent with the viability of the drying operation and with the ignition temperature value measured to avoid waste property loss.

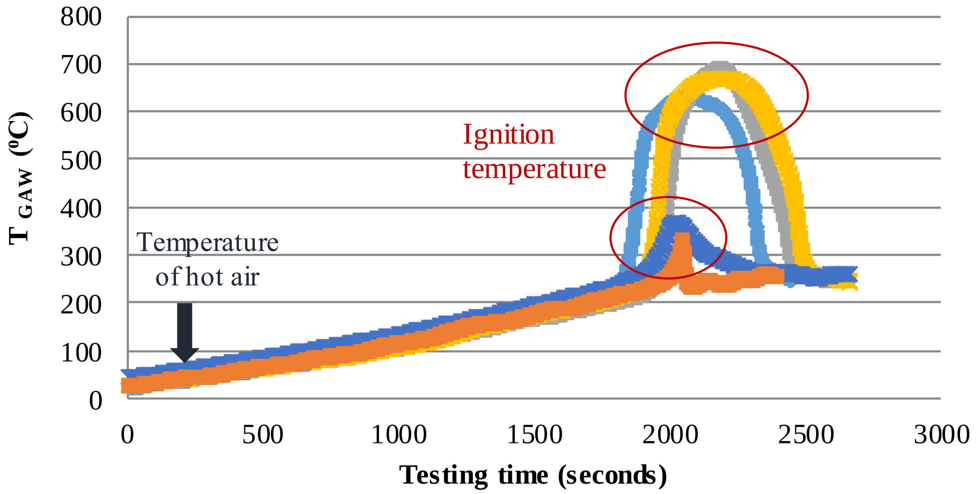

Figure 6. Evolution of the temperature in GAW samples during the ignition temperature test. Determination of ignition temperature of GAW.

Pressing was performed in a vessel made especially for this purpose. It consists of a stainless-steel vessel with small holes in the surface through which the leachates from the washed waste can flow outward during pressing. The aim of this operation is to remove the major quantity of moisture present in the GAW before drying. Figure 7 shows the vessel where took place the pressing of GAW samples.

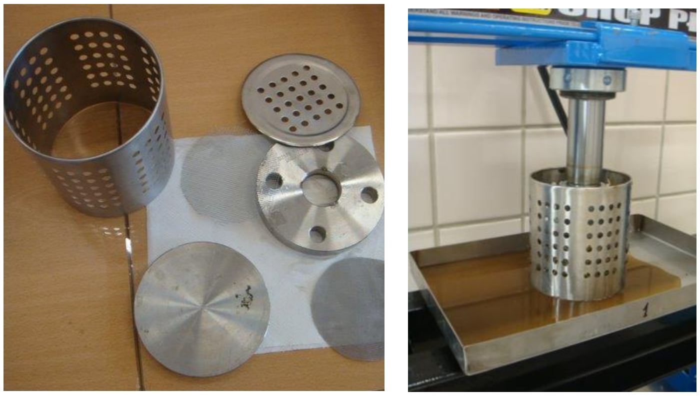

Figure 7. (Left) Details of vessel made for pressing of GAW samples. (Right) Pressing of GAW sample.

Results and Discussion

The cement plant studied in this work is located in the Almeria region (Spain). This installation produces clinker using the dry process technology with a 4-stage preheater, a long rotatory kiln with a multichannel burner and a grate cooler for cooling the clinker produced. The main fuel used in this plant is pet coke, which provides 70% of the total thermal energy consumed by the rotatory kiln. The rest of the energy requirements are covered with alternatives fuels (AFRs) such a solvents, oils and asphalts, fine solids and bulk solids.

The Integrated Environmental Authorisation (IEA) of this cement plant defines the key parameter limit values required for the combustion of new AFR in the burner of the rotatory kiln. In this case, these values are less than a 0.8 % wt. for chlorine content, less than 3.0 % wt. for sulphur content and higher than 6,270 kJ/kg for LCV. The moisture content is not defined in this document, but experience recommends a value lower than 8.0% wt. to carry out an efficiency combustion process. Ash content is also not defined in the IEA. However, a low ash content is desired when a fuel is going to be burn in a process.

Once the physico-chemical characterization of the GAW samples was obtained in the laboratory, a list of the different sequences of operations was defined to carry out the conditioning of these wastes. This list was created from a practical and economical point of view, so the operations, which make up each sequence, are simple and well known because of their common application in a large number of chemical processes.

Table 1 describes the pretreatment systems defined and tested at the ETSI laboratory.

Table 1. Pretreatment systems defined for the laboratory testing.

Pretreatment system code	Sequence of operations
T-02 - Reference	Tg/ M/ Sc/ D
T-04	Tg/ M/ Sc/ W (R= 1:1/ t= 0.5-5/ T= 25)/ P/ D
T-05	Tg/ M/ Sc/ W (R= 1:2/ t= 0.5-5/ T= 25)/ P/ D
T-06	Tg/ M /Sc /W (R= 1:3/ t= 0.5-5/ T= 25) / P/ D
T-07	Tg/ M/ Sc/ W (R= 1:5/ t= 0.5-5/T= 25) /P/ D
T-08	Tg/ M/ Sc/W ($R_{Opt.}$/ $t_{Opt.}$/ T= 35) / P/ D
T-08’	Tg/ M/ Sc/ W ($R_{Opt.}$/ $t_{Opt.}$/ T= 45) / P/ D
T-09	Tg/ M/ Sc/ P/ W ($R_{Opt.}$/ $t_{Opt.}$/ $T_{Opt.}$) / P/ D

Tg: triage operation; M: milling operation; Sc: screening operation; W: washing operation; P: pressing operation; D: drying operation; R: ratio of washed (kilogram of waste per kg of water); t: time of washed (minutes); T: temperature of water (ºC); $R_{Opt.}$: optimal ratio of washed; $t_{Opt.}$: optimal time of washed and $T_{Opt.}$: optimal temperature of water.

The pretreatment T-02 was considered the reference case to assess the efficiency of the rest of the sequence of operations. This system consisted of a triage, a milling, a screening and a drying of each sample of GAW received in the laboratory. Triage and milling operations were carried out in waste treatment plant before samples were collected. For drying of the waste was used an air at a temperature close to 85ºC, lower than the average of temperature value measured in the specific ignition test ($\left.\bar{T}_{ignition}\right]_{GAW} \approx 450$ ºC) (Figure 6).

Pretreatments T-04 to T-07 included a controlled washing operation of the GAW in addition to the previous operations. This washing is carried out using demineralized water in different volumes per kilogram of waste fed to the system (R = 1:2; 1:3; 1:5) combined with different residential times (t = 0.5 – 5 min) and a water temperature of approximately 25 ºC.

Pretreatments T-08 and T-08’ were assessed with the optimal value of the ratio of washed ($R_{Opt.}$) and residential time ($t_{Opt.}$). In addition, a water was used with a temperature ~~of~~ varying from 35ºC to 45ºC, respectively. These pretreatments allowed the selection of the optimal value of the wash water temperature ($T_{Opt.}$).

Finally, pretreatment T-09 included an additional pressing operation before washing the GAW sample to assess its impact on the removal of the chorine content. To this end, the ratio of washed, the residential time and the temperature of the wash water were the optimal values identified in the previous pretreatment tests.

Figure 8 shows the systems’ setup installed for carrying out the different pretreatment tests at the ETSI laboratory.

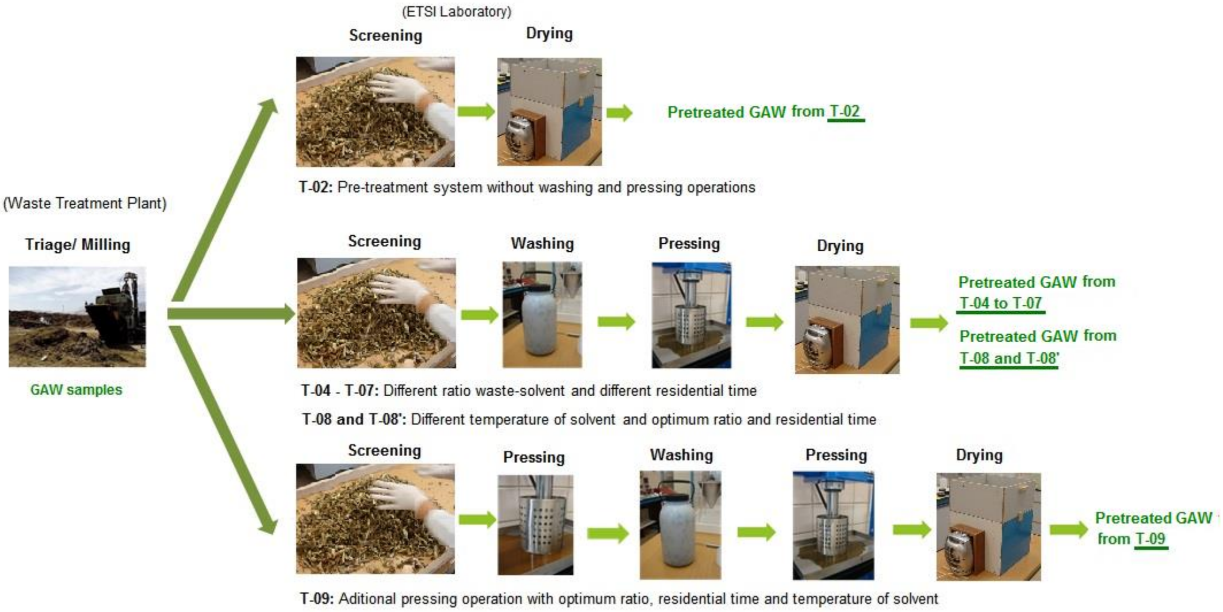

Figure 8. Scheme of the pretreatment systems from reception of GAW in the waste treatment plant to the production of a pretreated GAW from each pretreatment system assed at the ETSI laboratory.

A sample of the pretreated GAW was obtained from each pretreatment test. The average chlorine content and moisture content associated with the pretreated GAW through each sequence of operations is shown in Figure 9 and Figure 10.

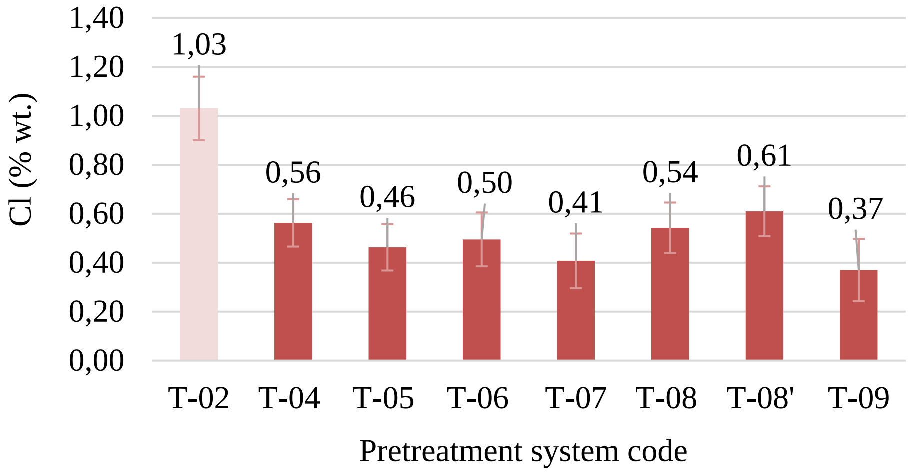

Figure 9. Average chlorine content expressed % wt. dry bases, in the pretreated GAW obtained in each pretreatment system tested at the laboratory.

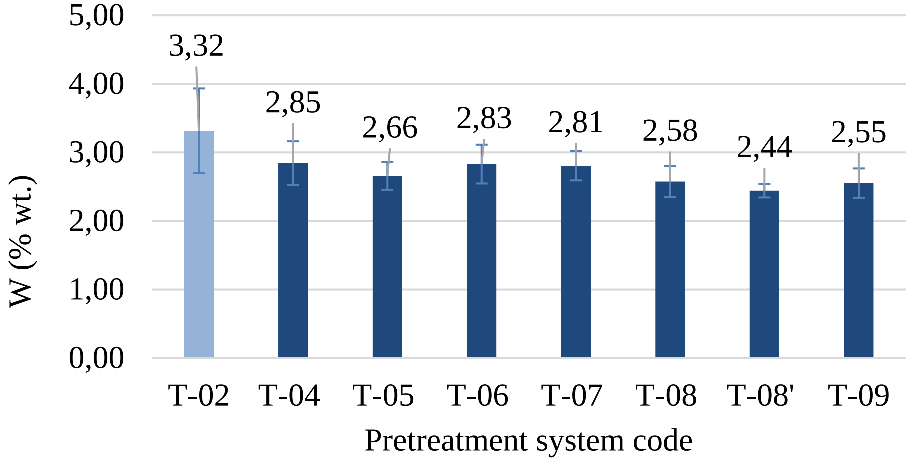

Figure 10. Average moisture content expressed % wt., in the in the pretreated GAW obtained in each pretreatment system tested at the laboratory.

According to the chlorine content results, it could be considering essential to implement a washing operation to decrease the chorine level in the GAW. All the pretreatment systems that include this operation reduced the chlorine content by approximately 50% of the initial content, but it is important to examine all options to select those with a suitable consumption of water. Pretreatments T-04, T-05, T-06 and T-07 used different volumes of water for washing the same quantity of waste. In particular, pretreatment T-04 used 1 kg of water per 1 kg of agriculture waste (R=1:1); pretreatment T-05 used 2 kg of water per 1 kg of agriculture waste (R=1:2); pretreatment T-06 applied 3 kg of water per 1 kg of agriculture waste (R=1:3); and pretreatment T-07 employed 5 kg of water per 1 kg of agriculture waste (R=1:5). In all cases, the temperature of the water ~~is~~ was 25ºC.

Considering this aspect and paying attention to the similar chlorine reduction percentages achieved by these pretreatment systems, it is assumed that the best ratio for carrying out an efficient washing of waste is the R= 1:2 ratio, associated with the T-05 pretreatment. In this case, the volume of water impregnated the waste sample properly, facilitating the handling of the GAW during the washing and the subsequent operations. At the same time, it was evaluated as the optimal time for carrying out this washing. During the testing, the chlorine content in the wash water was controlled, understanding the values obtained as an indirect measurement of the capacity of the wash water to remove the chlorine content of the waste. Beginning in the first minute, the chlorine content in the wash water remained constant, so only 1 minute was needed to complete an adequate washing of the waste.

Pretreatments T-08 and T-08' were evaluated with a ratio of 1:2 and a residential time of 1 minute. The difference between them was in the temperature of the water employed for washing the waste. In the first case, the water was heated up to 35ºC, while in the second case, the water temperature was 45ºC. In these conditions, the chlorine content measured in the pretreated GAW were higher than that in pretreatment T-05, in which the water used was at room temperature. For this reason, the optimal temperature of the water was then established at 25ºC.

As shown in Figure 9, an additional pressing operation (T-09) could be a good option when the GAW show a moisture content higher than 80% which usually happens during the wettest months (from November to January). The final chlorine content in the wastes after being conditioned by pretreatment T09 was reduced up to 35% wt. of the initial chlorine content.

Regarding the moisture content, Figure 10 shows that, in all cases, the samples reached an adequate moisture level (W < 8.0% wt.). For this reason, the best pretreatment system was selected considering the sequence of operations that remove the chlorine content of the GAW with a minimal energy and water consumption.

Table 2 shows the selected pretreatment systems for conditioning the GAW for its future use as an alternative fuel in the cement plant. Based on the initial moisture content in the waste, pretreatment T-05 was more accurate for an initial moisture content below 80.0% wt., while pretreatment T-09 was more adequate for an initial moisture content equal or greater than 80.0% wt.

Table 2. Selected pretreatment systems for conditioning the GAW as an alternative fuel considering the harvesting period.

Harvesting period of GAW	Moisture content of GAW (% wt.)	Pretreatment system code	Characteristics of the sequence operations
February - October	$W_{GAW} < 80.0$	T-05 (Tg/M/Sc/W/P/D)	**Triage/Milling** Conditions similar to implemented in waste treatment plant. **Screeaning → Rotatory drum screen** **Washing** Ratio (kg GAW/kg water) =1:2 t= 1 min T= 25ºC **Pressing → Mechanical press** P≈ 2,000 kg/cm^2; t= 2 min **Drying → Rotatory dryer** Hot air $T_{Hot\ air} \approx 80ºC < T_{GAW\ ignition}$
November - January	$W_{GAW} \geq 80.0$	T- 09 (Tg/M/Sc/P1/W/P2/D)	**Triage/Milling** Conditions similar to implemented in waste treatment plant. **Pressing 1 → Mechanical press** P≈ 2,000 kg/cm^2; t= 2 min **Washing** Ratio (kg GAW/kg water) =1:2 t= 1 min T= 25ºC **Pressing 2 → Mechanical press** P≈ 2,000 kg/cm^2; t= 2 min **Drying → Rotatory dryer** Hot air $T_{Hot\ air} \approx 80ºC < T_{Ignition}]_{GAW}$

Considering the previous pretreatment systems, it may be said that the average LCV associated to the pretreated GAW increase by around 16.0% with respect to the original average value. This increase is similar for both selected pretreatment, because including one additional pressure in the conditioning process only affects to the final content of chlorine in the pretreatment waste. The characteristic of the pretreated GAW obtained from each pretreatment systems shown in Table 3.

Table 3. Key properties of the pretreated GAW obtained from each selected pretreatment systems.

Pretreatment system code	$\mathbf{Cl_{Pret.GAW}}$ **(% wt. db)**	$\mathbf{W_{Pret.GAW}}$ **(% wt.)**	$\mathbf{S_{Pret.GAW}}$ **(% wt. db)**	$\mathbf{\overline{LCV}_{Pret.GAW}}$ **(kJ/kg)**
T- 05	$< 0.5 \cdot [Cl]_{GAW}$	< 3.0	< 5.0	15,800
T- 09	$< 0.35 \cdot [Cl]_{GAW}$	< 3.0	< 5.0	15,800

% wt. db: weigh percentage expressed on dry basis; $X_{Pret.GAW}$: Content of X (Cl, W or S) in the pretreated GAW; $\overline{LCV}_{Pret.GAW}$: Average LCV in the pretreated GAW; X_{GAW}: Content of X (Cl, W or S) in the GAW.

The expected values for the key parameters (Cl, W, S and LCV) given by both pretreatments should allow the use of the solid substrate generated as an alternative fuel in the cement plant.

According to the IEA (Integrated Environmental Authorization) of this plant and considering the alternative fuel amount introduced in the process at the time of this study, the maximum amount of a new alternative fuel that could be introduced into the kiln burner was 35,000 tons per year.

If this allowed alternative fuel amount is provided by pretreated GAW, a 51% of the thermal energy provided by fossil fuel (pet coke) could be replaced, keeping the flow of the rest of the alternative fuels fed to the rotatory kiln constant.

The pet coke substitution by GAW, which is considered as biomass waste with carbon-free production [26], could provide an important reduction of the total CO_2 emissions and therefore relevant financial savings.

The replacement of 51% of the thermal energy provided by the pet coke in the kiln of the cement plant evaluated in this work, is equivalent to provide 1.6 GJ per tons of clinker using pretreated GAW. This replacement could provide a saving of CO_2 emission of up to 0.16 tons of CO_2 per tons of clinker produced per year, associated with the equivalent reduction in the pet coke consumption.

In this sense, considering LCV value of pet coke consumed in this cement plant (LCV= 33,300 kJ/kg), emission factor of this fossil fuel (97.5 t CO_2/GJ_{LCV}) and average CO_2 emission cost in 2018 (15.88 €/t CO_2), the cement plant could be achieve financial savings derived of the decrease of CO2 emissions of up to 2.5 € per tons of clinker produced.

Conclusion

In this research study, different sequences of operations for conditioning agricultural wastes from greenhouses (GAW) of the west of Almeria (Spain) were evaluated at the laboratory scale. Each GAW sample analysed were collected in the waste treatment plant where these wastes are stored. The conditioning of collected GAW was necessary to use this kind of wastes as an additional alternative fuel in a cement plant located in this region. The main objective of the pretreatment system developed herein was to reduce the chlorine and the moisture content associated with the GAW to comply with the requirements demanded in the Integrated Environmental Authorization (IEA) of the cement plant. Washing these wastes with a ratio of 1 kg of GAW per 2 kg of water at room temperature and drying with hot air were sufficient to minimize the chlorine and the moisture content below 0.8% wt. and 8.0% wt., respectively, among other simple operations such triage, milling, screaming and pressing.

An energy recovery of 35,000 tons of pretreated GAW per year in the cement plant evaluated in this work, could replace the 51% of the thermal energy provided by pet coke, leading to a CO_2 emission savings of up to 0.16 tons of CO_2 per tons of clinker produced per year.

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Abbreviations

AFRs - Alternative Fossil Fuels; IEA - Integrated Environmental Authorization; Cl – Chlorine; S – Sulphur; W - Moisture; LVC - Low Calorific Value; R - Washed ratio; t - Time; T - Temperature; $R_{Opt.}$ - Optimal washed ratio; $t_{Opt.}$ - Optimal time; $T_{Opt.}$ - Optimal temperature; GAW - Greenhouse agricultural wastes.

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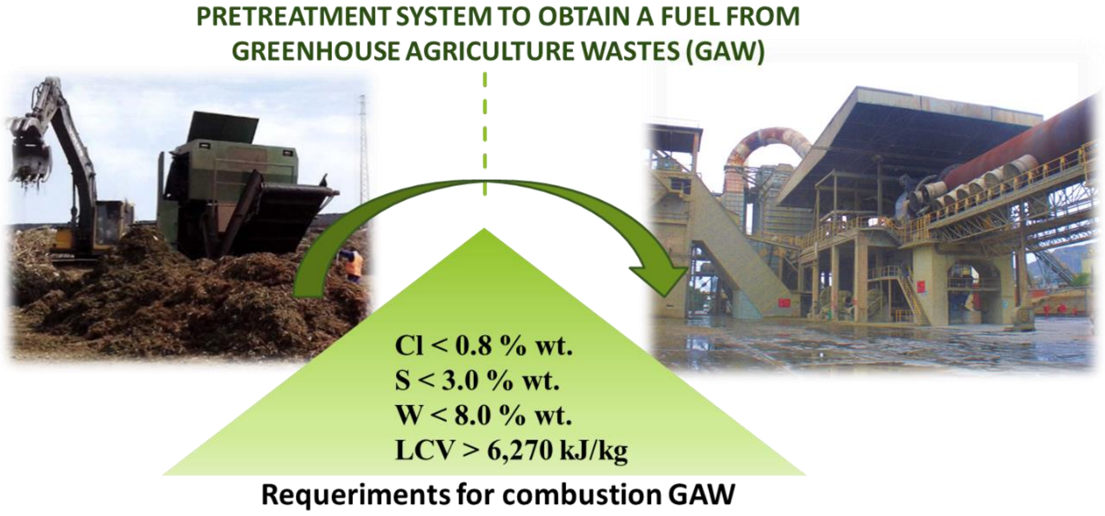

Synopsis

Pretreatment of greenhouse agricultural waste (GAW) produces a suitable alternative fuel which can contribute to promote the transition towards a cleaner industry in the context of a low carbon economy.