Cronfa - Swansea University Open Access Repository

Paper:

Cadavid-Rodríguez, L., Vargas-Muñoz, M. & Plácido, J. (2019). Biomethane from fish waste as a source of renewable energy for artisanal fishing communities. *Sustainable Energy Technologies and Assessments, 34*, 110-115.
http://dx.doi.org/10.1016/j.seta.2019.05.006

BIOMETHANE FROM FISH WASTE AS A SOURCE OF RENEWABLE ENERGY FOR ARTISANAL FISHING COMMUNITIES

L.S. Cadavid-Rodríguez[1]*, M.A. Vargas-Muñoz[1], J. Plácido[2]

1. Departamento de Ingeniería, Facultad de Ingeniería y Administración, Universidad Nacional de Colombia, Carrera 32 No 12-00, Palmira, Colombia

2. Institute of Life Science, Swansea University Medical School, Swansea University, Swansea, SA2 8PP, Wales, UK

ABSTRACT

The potential of biogas production from fish waste as source of renewable energy for fishermen communities was evaluated. Four different fish waste concentrations (1%, 1.5%, 2% and 2.5% total solids (TS)) were digested during 28 days at mesophilic conditions. Biochemical Methane Potential (BMP), volatile fatty acids (VFA) concentration and ammonia concentration were analysed during the experiment. Energy production and economic projections were performed to estimate the number of families that can benefit from the biogas production in Tumaco, Colombia. The 1% TS had the highest BMP (464.5 mL CH_4/g VS) and the lowest VFA production (2515 mg/L); in contrast, the 2.5% TS had the highest VFA production (11302 mg/L) and the lowest

---

* Corresponding author.
E-mail address: lscadavidr@unal.edu.co
Phone: (57-2) 2868888 Ext: 35709

methane production (206.86 mL CH_4/g VS). The treatments with 1.5%, 2% and 2.5% TS exhibited diauxic growth as result of different solubilisation rates in the fish waste components. The energetic and economic analyses estimated a yearly energy production of 489 MWh, which can satisfy the electric energy consumption or the cooking energy demand of 230 fishermen families. The results showed that biogas production from fish waste is a viable and sustainable alternative to adequately manage this material and provide renewable energy to fishermen communities.

Key words: Anaerobic digestion; fish waste; biogas; renewable energy; artisanal fishers.

1 INTRODUCTION

Colombia produces approximately 230.000 tons of fish every year, from which 80.000 tons are from fish farming and 150.000 tons from industrial and artisanal fishing [1]. Artisanal fishing includes the small scale, low technology and low capital fishing practices performed by fishing households. Colombia has between 67.000 and 150.000 artisanal fishers [2] which are responsible for supplying 75% of the whole Colombian fish market [3]. Tumaco, the second largest city on the Colombian Pacific coast, is one of the most dynamic artisanal fishing centres. Tumaco produces more than 1.000 tons of fish per year and has an artisanal fishing production that accounts for 9% of the production of artisanal fisheries in the country [4]. As a zone affected by the Colombian armed conflict, Tumaco and its population are under persistent social, economic and environmental issues.

One of the main environmental and economic issues affecting artisanal fishers is produced by fish waste (FW). Artisanal fishermen produce FW mainly from traditional practices during fish catching and processing. During fish catching, the viscera are thrown directly into the sea during prolonged fishing operations. whereas in fish processing, generally at the commercialisation sites, skin, bones and other residues are produced and disposed into the ocean or landfills. It is estimated that around 45% of the total fish production corresponds to fish waste (FW) [5], representing significant economic losses for this sector. Besides the economic losses, inadequate FW disposal generates high loads of organic matter with high degradation potential, which affects aquatic ecosystems, produces greenhouse gases and bad odours [6]. This, in turn, favours the proliferation of vectors and the transmission of intestinal diseases (dysentery, diarrhoea and gastritis) and endemic diseases (malaria, yellow fever and dengue) [7] endangering the communities in Tumaco.

Currently, FW from industrial fishing is used for low-value animal feed products, through the production of fishmeal, silage and fertilizers [8]. In recent years, Anaerobic Digestion (AD) appears as a promising technology for the environmentally safe transformation and management of FW [9-11]. Generally, AD is defined as a biological process carried out in absence of oxygen where the biomass is degraded and stabilised by a microbial consortium to produce methane, a product used as a source of renewable energy. Besides methane other authors have reported the transformation of FW into other added-value products, such as volatile fatty acids, oils and proteins [8, 12, 13].

FW is a heterogeneous waste rich in proteins and lipids compounds that facilitates the production of high methane yields [14]. But at the same time, FW releases components such as free long chain fatty acids, high amounts of ammonia and high concentrations of light metals such as calcium, sodium, potassium and magnesium, that affects the anaerobic degradation [15]. Biomethane production from fish waste has been evaluated in direct digestion and in co-digestion with other wastes. Biomethane using exclusively FW has been produced from residues such as gilthead seabream FW sludge (361 Nm^3 CH_4 Mg VS^{-1}) [11], saline fish waste (428 mmol CH_4 kg COD^{-1} day^{-1}) [16], offal fish waste (164.7 L CH_4 kg COD^{-1}), fish canning facilities (0.59 g COD–CH_4 g COD^{-1} and 441–482 mL g VS^{-1}) [12, 17] and sturgeon heads and viscera (1.4 L CH_4 g VS^{-1}), [18], [19]. FW co-digestion has produce biomethane from mixtures of strawberry and FW (0.205 m3 CH4 kg VS^{-1}) [20], FW and bagasse (409.5 mL g VS^{-1}) [21], FW and sisal pulp (0.62 L CH_4 g VS^{-1}) [22] and FW and cow manure (0.4 L CH_4/g VS) [23, 24]. The previous research in biomethane production from FW evidenced the need of an inoculum adapted to low C:N ratios, a positive effect by adding nutrient rich materials and variable methane production depending of the FW type. However, the production of methane from FW has not focused in fish wastes from artisanal fishers and the further application of this waste to supply the energy requirements for in-need communities such as Tumaco's artisanal fishermen households. Artisanal FW has higher solids and nitrogen concentrations than industrial FW, these differences can generate differences in the retention times, biomethane production and nitrogen concentrations than previously reported FW.

Therefore, to solve the energy and waste management requirements in the fisherman communities in Tumaco, Colombia, the aim of this study was to evaluate the production of renewable energy, in the form of biogas, from artisanal fish wastes from Tumaco, Colombia and to estimate the energy production and the number of families benefited by transforming Tumaco's fish waste into biogas.

2 MATERIALS AND METHODS

2.1 Inoculum and substrate

The inoculum was a methanogenic inoculum (MI) obtained from an upflow anaerobic sludge blanket (UASB) reactor treating wastewaters from the slaughterhouse plant of *Carnes y Derivados de Occidente SA*, (Candelaria, Colombia). The FW was collected from artisanal fishers from the port of Tumaco (Nariño, Colombia) and consisted principally in guts, digestive tracts and viscera from a mixture of different types of fish species including red snapper, corvine and tuna. After collection, FW was transported to the laboratory in a 4 °C refrigerated container. The transportation process between collection and cold storage in the laboratory had a duration of 4 hours. In the laboratory, the samples were ground to 5 mm particle size using a food processor (Black & Decker FP1336) and then frozen until use.

2.2 Experimental set-up

In order to determine the biogas production, the standardised Biochemical Methane Potential (BMP) test was carried out according to Owen et al. (1979) [25] and Angelidaki et al. (2009) [26]. Duran bottles of 250 mL with an effective volume of 210 mL and rubber stoppers provided with a valve for methane measurement were used. The effect of FW concentration on methane production followed a completely randomised experimental design with four levels and three replicates. The four FW total solid (TS) concentrations were 1%, 1.5%, 2% and 2.5% TS. The experiments were carried out using an FW to inoculum ratio of 1:1, in terms of Volatile Solids (VS) during 28 days at 37±2 °C, without pH control and with manual agitation once a day. Methane production, Volatile fatty acid (VFA) concentration and ammonia concentration were used as response variables. Methane production was measured daily and the methane volumes were corrected by subtracting the mean methane volume of the inoculum control and were converted to standard temperature and pressure (STP, 0°C and 760 mm Hg). VFA and ammonia were measured from 5 mL samples procured from the experimental units at days 1, 7, 14, 21 and 28. Then, the samples were centrifuged at 3000 rpm for 20 minutes (centrifuge brand) and finally refrigerated at 4°C until analysis. The experiment included two bottles with inoculum and without FW as control. The BMP results at day 28th were analysed in a one-way ANOVA and the Duncan's means tests. The statistical analysis was performed with the GLM procedure of the SAS Software University Edition.

2.3 Analytical methods

The inoculum and substrate characterisation, as well as the analysis of total VFA and ammonia were carried out following the protocols of the APHA standardised methods [27]. Total solids (TS) dried at 103-105 °C (method 2540 B), Fixed and volatile solids (VS) ignited at 550 °C (method 2540 E), Titrimetric method for ammonia (method 4500-NH_3 C). Distillation method for VFA (method 5560 C). Titrimetric method for alkalinity (Method 2320 B) and Closed reflux, colorimetric method for COD (method 5220 D). The production of VFA and ammonia was determined with a Kjeflex K-360 Buchi distiller. The carbon and nitrogen contents of the inoculum and FW were determined using the ASTM D 5373 standard from 2014.

The daily biogas production was measured with the water displacement technique using a Mariotte bottle. In selected samples, the methane and carbon dioxide content were analysed using gas chromatography ((GC) *Agilent Technologies* 6890[a] with a Hewlett Packard 7694E static headspace device, thermal conductivity detector and flame ionisation detector (S-HS/GC /TCD/FID)). The chromatographic analysis was performed with a monolithic carbon column (30 m x 0.53 mm x 3 µm) and a zeolite (30 m x 0.53 mm x 50 µm) column.

3 RESULTS AND DISCUSSION

3.1 Physicochemical characterisation of MI and FW

Table 1 describes the characterisation of the FW collected from the artisanal fishers in Tumaco and the Methanogenic inoculum from the UASB reactor from the slaughterhouse plant. FW had a mixture of liquid and solid compounds (25.2% TS) with high organic matter content (88.9% VS in dry basis) and high nitrogen content (8.84% TKN in dry basis). Tumaco's artisanal FW had similar characteristic as FW reported from fish canning facilities which had TS% between 20% and 40% and VS% between 73% and 95% [12, 19, 20]. FW from fish farms doubled the amount of total solids (50%) compared with Artisanal FW and Fish canning wastes, however, fish farms FW has a similar VS% as artisanal FW (88-90%) [17]. The significant amounts of biodegradable materials in the artisanal FW have been associated with the production of biogas from FW in other investigations [12, 19]. The majority of biodegradable materials in FW are lipids (5–55%) proteins (40–75%) and carbohydrates (5–13%) [23, 28], materials successfully transformed into biogas using anaerobic digestion; although, the high protein and lipids content can reduce the methane yield. The methanogenic inoculum had a high VS (84.9 % in dry basis) and high nitrogen content (8,9 % NTK in dry base) reflecting a significant amount of microbial biomass and residual nitrogen from the UASB reactor employed for treating slaughterhouse wastes. The considerable amount of ammonia in the artisanal FW and the MI conferred the fermentation broth with a high buffer capacity. The low C/N ratio of the substrate and the inoculum is similar to the values observed in previous biomethane from fish waste processes and it was associated with the production of higher concentrations of ammonia during digestion.

3.2 Anaerobic digestion of artisanal Fish Waste

3.2.1 Methane production from artisanal FW

Methane production from artisanal FW (cumulative and production rate) is depicted in **Figure 1.** All the artisanal FW concentrations had a high methane yield during days 1 and 2 of the experiment. This initial peak was the highest methane production rate observed in all the treatments. The 1.5, 2 and 2.5% TS treatments reached the highest rate (43.58, 75.5, 43.14 mL CH_4 g VS^{-1} d^{-1}) during the first day; whereas, 1% TS treatment reached the highest production rate during the second day (48.5 mL CH_4 g VS^{-1} d^{-1}). In all cases, on day 3, the methane production reduced between 50 and 100%. After this, the 1% treatment kept its methane production between 12 and 25 mL CH_4 g VS^{-} d^{-1} until day 20, when the methane production started to decrease. In contrast to 1%TS treatment, the treatments with 1.5, 2 and 2.5% TS evidenced a constant but low production of methane after day 3. The duration of this constant phase was dependent of the FW concentration (1.5% 10 days, 2.0% 13 days, 2.5% 20 days) and was followed by an increment in the methane production or a constant methane production until the end of the experiment (**Figure 1**). After the initial methane production peak, in average, the lowest methane production rate was observed on the concentration with 2.5% TS (6 mL CH_4 g VS^{-1} d^{-1}), followed by 2% TS (12 mL CH_4 g VS^{-1} d^{-1}) and 1.5 and 1 % TS (14 mL CH_4 g VS^{-1} d^{-1}). Although, the methane production rate of the 1% TS treatment was higher in the initial days, it was lower than that of 1.5% TS treatment at the end of the fermentation process. The presence of a high production peak in the initial days has been reported in FW from canning facilities and fish farming and has been associated with the transformation of substrates that were easy to digest from the FW or the inoculum [17, 19]. Similar to artisanal FW, a second increment in the methane production rate was also reported in the production of biomethane from mackerel fish waste and cuttlefish waste [19]. The methane production inhibition observed in the high concentrations (2.5 and 2 % TS) were also described in fish canning wastes (2.5 and 5% TS), FW and strawberry wastes co-digestion, and FW and cow manure co-digestion (19% FW) [12, 20, 23]. Besides FW initial load, the FW to inoculum ratio (F/I) has been a factor influencing methane production from FW. FW and sisal pulp co-digestion, fish canning wastes and fish farm wastes reached the highest yields using an F/I of

0.5. Similar to Artisanal FW, F/I ratios of 1 had better performances in FW from 4 different types of fish [12]. The different results in the FW literature can be explained by the differences in temperature, the F/I ratio and the intrinsic differences associated with the fish species. The species from which the fishing residue comes is also a factor to be taken into account, since Eiroa *et al.*, (2012) [12] reported methane potentials of: 0.25 L CH_4/g SV_{added} for sardine waste, 0.26 L CH_4/g SV_{added} for needle fish waste, 0.28 L CH_4/g SV added for tuna waste and 0.35 L CH_4/g SV_{added} for mackerel waste.

The cumulative methane production profile was different in all the treatments. The 1 % TS treatment exhibited a unique production phase achieving a BMP value of 464.5 mL CH_4/g VS. In contrast, the concentrations of 1.5%, 2% and 2.5% TS exhibited two methane production phases during the experiment producing a total BMP of 452.6 mL CH_4/g VS, 425.2 mL CH_4/g VS and 206.9 mL CH_4/g VS, for the TS concentrations of 1.5, 2 and 2.5%, respectively. The presence of a second phase evidenced that the fermentation broth has an easier biodegradable fraction and a more complex fraction that requires a longer period of hydrolysis, resulting in diauxic growth [29]. In FW, proteins have a relatively high solubilisation rate, while that of lipids is relatively low [30]. In fact, during the first days of the experiments, an immiscible layer of fat and its degradation products was observed in the upper part of the reactors. The disappearance of this phase was a proof of the FW heterogeneity producing diauxic growth in the reactor. Diauxic growth behaviour has been observed in the methane production from pacific saury fish waste, mackerel fish waste and cuttlefish waste, however, these fermentations had a longer duration than the process reported in this article with artisanal fish wastes [19]. Similar to FW, the AD of other heterogeneous substrates had evidenced diauxic growth, for example, the digestion of wastewater screenings [31]. In the future, to improve the production of biogas from artisanal FW is necessary to evaluate economic methods to achieve rapid solubilisation and hydrolysis of fats. These methods will help to avoid the accumulation of long-chain fatty acids (LCFA). LCFA can accumulate in reactors affecting metabolic transport and generating methane production inhibition [32].

A one way ANOVA was performed using the BMP results from day 28. The ANOVA evidenced the presence of significant differences among the treatments with a *p-value* below the alpha (0.05>0.0010) (Supplementary Material). As the ANOVA proved differences among the treatments, the Duncan's means test was used to see how different the treatments were (**Figure 2**). The treatments with 1 and 1.5% did not have significant differences; however, they were different from the treatments with 2 and 2.5%. The treatments with 2 and 2.5% were also different between each other. This indicates that it is possible to use a TS value of 1 or 1.5% to produce similar amounts of BMP, however, 1% TS reached the maximum production faster than the others concentrations.

3.2.2 Volatile fatty acids and ammonia production from artisanal FW

The ammonia concentration during the AD of Tumaco's artisanal FW is depicted in **Figure 3.** The ammonia concentration profiles were opposite to methane production, as the treatments with the highest initial FW concentration exhibited the highest ammonia concentrations. The highest amounts of ammonia observed in each treatment were 943, 730, 542, and 431 mg NH4+ L^{-1} for the 2.5, 2, 1.5 and 1 % TS treatments, respectively. In all treatments, the ammonia had the most significant increment during the first week of digestion and was associated with the steep reduction in methane production observed after the third day of the digestion (**Figure 1**). After this initial increment, the ammonia concentration was almost constant for the treatments with 1, 1.5 and 2 % TS. The 2.5% concentration experienced a second increment in the ammonia concentration during the 21st day of digestion. This increment was also associated with a reduction in methane production (**Figure 1**). The lowest methane production observed in the 2.5% ST can be explained by the high ammonia concentrations (between 705 and 944 mg/L) during the whole process (**Figure 3**). The anaerobic digestion of wastes with high concentrations of solids has been inhibited by the accumulation of ammonia released by protein hydrolysis [15, 33]. In fact, it has been reported that ammonia concentrations greater than 800 mg L^{-1} are inhibitory for anaerobic processes. In alkaline conditions, ammonia is in its free form and easily permeates the bacterial cell wall, causing a toxic effect [32, 34].

The anaerobic digestion of artisanal FW achieved the production of significant amounts of VFA (**Figure 4**). All FW concentrations reached a VFA production above 2.000 mg L^{-1}. The 2.5% TS treatment obtained the highest VFA concentration (11.302 mg L^{-1}) followed by the TS concentrations of 2%, 1.5% and 1% TS with VFA concentrations up to 8.918 mg L^{-1}, 5.090 mg L^{-1} and 2.515 mg L^{-1}, respectively. Similar to ammonia concentration, VFA concentration was opposite to methane production as the treatments with the highest initial load produced the highest VFA concentration. In all FW concentration, the VFA production had the most significant increment in the initial 7 days; however, the maximum VFA concentration was reached after 14 days of digestion. The high VFA production during the initial days related to the reduction in methane production. The ammonia and VFA concentrations caused a reduction in the BMP of the highest TS concentrations. High protein wastes produce excessive amounts of ammonia and VFA as the anaerobic degradation of amino acids follows the Stickland's reaction and the two mayor products from this reaction are ammonia and VFA. In methane production excessive VFA accumulation produces a decrease in the pH and an affectation of methanogenic microorganisms [15]. Non-ionised VFA inhibit methanogenic activity, when acid production rates exceeds the consumption rates. The VFA concentration achieved by the artisanal FW with 2.5% concentration was higher than other FW at the same concentration, the difference in VFA production between artisanal and fish wastes is associated to the higher nitrogen concentration observed in artisanal FW than other FW reported in the literature. In other substrates, higher nitrogen concentration is associated with the production of higher amounts of VFA [35]. The production of high VFA concentrations evidence the potential of artisanal FW as raw material for the production of VFA similar to other high protein wastes such as slaughterhouse blood [35, 36].

3.3 Energy and economic projection in the city of Tumaco

The results from this research evidenced the potential for using artisanal FW as a source for methane production. Renewable energy sources are fundamental for the communities in Tumaco because the groups outside the law frequently attack the electric infrastructure generating lack of electricity to power Tumaco's population. **Table 2** summarise the economic analyses performed in the article. Between March and December of 2017, the artisanal fish landed in Tumaco was 942.4 tons [4]. Assuming a monthly fish landing average of 94.24 tons, for the whole year, the fish landed would reach approximately 1.131 tons. Therefore, considering that around 45% of the landed fish becomes FW [5]. Tumaco had an estimated production of 509 tons of FW per year. To estimate Tumaco's FW biogas potential the maximum biogas potential achieved in this study (714.62 L biogas kg VS^{-1}, 62% CH_4) was used. Assuming that it is possible to collect the total amount of FW produced (509 tons) it would be possible to generate 81,488 m^3 of biogas/year, equivalent to 489 MWh. This number was calculated by using an average biogas energy content of 6 kWh m^{-3} [37]. Likewise, assuming a biogas conversion efficiency to thermal and electrical energy of 45% and 35%, respectively [38], up to 220 MWh of thermal energy or 171 MWh of electric power could be obtained per year.

if all the biogas were purified and used to produce electricity, almost 230 homes could be supplied with basic electricity consumption, which averages 62 kWh per month [39]. If all biogas production were exclusively used for cooking, up to 230 families could supply their average basic consumption of 18 m^3 of propane gas per month (equivalent to 27 m^3/month of biogas) [40]. If biogas from FW were used for cooking each fishermen household will save around USD $204 and Tumaco's artisanal fishermen community would save around USD $ 47.000 per year. This calculation is based in the fact that families in Tumaco must buy propane or firewood for cooking and it has an average price per month of USD $ 17. As 42 kg of FW (89% VS) are necessary to produce 27 m^3 of biogas per month, a 6 m^3 reactor (4.5 m^3 work volume and 1.5 m^3 for gas storage) is required to maintain the optimum FW concentration (1% TS). A program for using FW to supply the cooking energy demand of Tumaco's fishermen households can have an estimated cost between 700 and 1.700 USD for household. This cost includes the installation of an 8-6 m^3 plug flow digester (Plug flow digesters do not require mechanical mixing and can be constructed by the fisherman household for reducing costs) with a life span of 15 years with an estimated capital cost between 500 and 1.500 USD [41]. The cost also includes the (~200 USD) artisanal fishermen training for starting and maintaining the digesters (30 days HRT) and a 5 USD for water costs (0.2 USD per 1 m^3 of water). The initial cost for this renewable energy and waste management program in Tumaco have a payback period between 3 and 8 years for each household. The total cost of this type of program for the National, state or city government is between 115.000 and 345.000 USD which is a low number compared with the cost associated with the negative effects produced by mismanaging FW. Programs focused in changing the consumption of propane and firewood for cooking will reduce the respiratory diseases caused by the combustion of firewood, the production of greenhouse gases and the deforestation of mangroves around Tumaco.

4 CONCLUSIONS

The results of this investigation demonstrated the potential for using artisanal fish waste as a substrate for methane production and provided a scientific and economic basis for developing programs to utilise biomethane from FW to supply the energy demands of the artisanal fishermen households in Tumaco, Colombia. Methane production from FW was possible at concentrations up to 2% TS at mesophilic conditions (35-37 °C) with a Methane potential between 0.25 - 0.5 L CH_4 g VS^{-1}. The highest BMP was obtained at a FW concentration of 1% TS (464.5 mL CH_4 g VS^{-1}), higher concentrations had lower BMP as they were inhibited by the ammonia and VFA accumulation. The treatments with 1.5, 2 and 2.5% TS exhibited diauxic growth as fats and proteins had a different hydrolysis rate in the digester. It was estimated that Tumaco's annual FW production (509 tons per year) can produce an energy potential of 489 MWh per year and can be a solution for supplying the energy cooking demand of more than 200 artisanal fishermen households. This research is the first step for establishing anaerobic digestion of FW as a solution for managing Tumaco's FW and for improving artisanal fisherman health, and Tumaco's environment and economy.

5 ACKNOWLEDGMENTS

The authors would like to thank the financial support provided by Newton Fund Institutional Links grant (275880329: 'Development of a bio-refinery system for organic acid production, bioenergy generation and nutrient recovery using fish wastes from Tumaco, Colombia') delivered by the Administrative Department of Science, Technology and Innovation from the Colombian government (COLCIENCIAS). Dr Jersson Plácido would like to thank the European Regional Development Fund/Welsh Government funded BEACON+ research programme (Swansea University).

6 REFERENCES

[1] Medina M. ENTREVISTA CON OTTO POLANCO: Colombianos consumen 10 kilos de pescado al año. El espectador 2018; Economia.

[2] OCDE. Pesca y acuicultura en Colombia 2016; November 2018: 31.

[3] Rodríguez Salcedo J, Hleap Zapata JI, Estrada F, Clavijo Salinas JC, Perea Velazco N. Agroindustria pesquera en el pacífico Colombiano: Gestión de residuos pecuarios en sistema de producción más limpia. Palmia, Colombia: Universidad Nacional de Colombia sede Palmira; 2011.

[4] De la Hoz-M J, Duarte LO, Manjarrés–Martínez L. Estadísticas de desembarco y esfuerzo de las pesquerías artesanales e industriales de Colombia entre marzo y diciembre de 2017. Autoridad Nacional de Acuicultura y Pesca (AUNAP), Universidad del Magdalena 2017: 84.

[5] Rai AK, Swapna HC, Bhaskar N, Halami PM, Sachindra NM. Effect of fermentation ensilaging on recovery of oil from fresh water fish viscera. Enzyme and Microbial Technology 2010; 46: 9-13.

[6] AUNAP. Plan Estratégico Institucional 2014-2018. Autoridad Nacional de Acuicultura y Pesca (AUNAP) 2013: 51.

[7] DIRENA. Plan estratégico y operativo del sector de la pesca artesanal del Pacífico nariñense. programa de Desarrollo con Identidad Regional entre España y Nariño DIRENA 2016: 218.

[8] Nges IA, Mbatia B, Björnsson L. Improved utilization of fish waste by anaerobic digestion following omega-3 fatty acids extraction. Journal of Environmental Management 2012; 110: 159-65.

[9] Tomczak-Wandzel R, Levlin E, Ekengren Ö. Biogas production from fish wastes in co-digestion with sewage sludge 2013.

[10] Choe U, Mustafa AM, Lin H, Xu J, Sheng K. Effect of bamboo hydrochar on anaerobic digestion of fish processing waste for biogas production. Bioresour Technol 2019.

[11] Greggio N, Carlini C, Contin A, Soldano M, Marazza D. Exploitable fish waste and stranded beach debris in the Emilia-Romagna Region (Italy). Waste Management 2018; 78: 566-75.

[12] Eiroa M, Costa JC, Alves MM, Kennes C, Veiga MC. Evaluation of the biomethane potential of solid fish waste. Waste Management 2012; 32: 1347-52.

[13] Bermúdez-Penabad N, Kennes C, Veiga MC. Anaerobic digestion of tuna waste for the production of volatile fatty acids. Waste Management 2017; 68: 96-102.

[14] Cirne DG, Paloumet X, Björnsson L, Alves MM, Mattiasson B. Anaerobic digestion of lipid-rich waste—Effects of lipid concentration. Renewable Energy 2007; 32: 965-75.

[15] Chen Y, Cheng JJ, Creamer KS. Inhibition of anaerobic digestion process: A review. Bioresour Technol 2008; 99: 4044-64.

[16] Quinn BM, Apolinario EA, Gross A, Sowers KR. Characterization of a microbial consortium that converts mariculture fish waste to biomethane. Aquaculture 2016; 453: 154-62.

[17] Chen X, Romano RT, Zhang R. Anaerobic digestion of food wastes for biogas production. International Journal of Agricultural and Biological Engineering 2010; 3: 61-72.

[18] Hadiyarto A, Budiyono B, Djohari S, Hutama I, Hasyim W. THE EFFECT OF F/M RATIO TO THE ANAEROBIC DECOMPOSITION OF BIOGAS PRODUCTION FROM FISH OFFAL WASTE. Waste Technology 2016; 3: 58-61.

[19] Kafle GK, Kim SH, Sung KI. Ensiling of fish industry waste for biogas production: A lab scale evaluation of biochemical methane potential (BMP) and kinetics. Bioresource Technology 2013; 127: 326-36.

[20] Serrano A, Siles JA, Gutiérrez MC, Martín MÁ. Optimization of anaerobic co-digestion of strawberry and fish waste. Appl Biochem Biotechnol 2014; 173: 1391-404.

[21] Xu J, Mustafa AM, Sheng K. Effects of inoculum to substrate ratio and co-digestion with bagasse on biogas production of fish waste. Environ Technol 2017; 38: 2517-22.

[22] Mshandete A, Kivaisi A, Rubindamayugi M, Mattiasson B. Anaerobic batch co-digestion of sisal pulp and fish wastes. Bioresource Technology 2004; 95: 19-24.

[23] Solli L, Bergersen O, Sørheim R, Briseid T. Effects of a gradually increased load of fish waste silage in co-digestion with cow manure on methane production. Waste Management 2014; 34: 1553-9.

[24] Solli L, Schnürer A, Horn SJ. Process performance and population dynamics of ammonium tolerant microorganisms during co-digestion of fish waste and manure. Renewable Energy 2018; 125: 529-36.

[25] Owen W, Stuckey D, Healy Jr J, Young L, McCarty P. Bioassay for monitoring biochemical methane potential and anaerobic toxicity. Water Res 1979; 13: 485-92.

[26] Angelidaki I, Alves M, Bolzonella D, Borzacconi L, Campos J, Guwy A, et al. Defining the biomethane potential (BMP) of solid organic wastes and energy crops: a proposed protocol for batch assays. Water science and technology 2009; 59: 927-34.

[27] American Public Health Association, APHA. Standard methods for the examination of water and wastewater: American public health association Washington, DC; 1995.

[28] Álvarez JA, Otero L, Lema JM. A methodology for optimising feed composition for anaerobic co-digestion of agro-industrial wastes. Bioresour Technol 2010; 101: 1153-8.

[29] Hamilton R, Casasús A, Rasche M, Narang A, Svoronos SA, Koopman B. Structured model for denitrifier diauxic growth. Biotechnol Bioeng 2005; 90: 501-8.

[30] Zhang B, Zhang L, Zhang S, Shi H, Cai W. The influence of pH on hydrolysis and acidogenesis of kitchen wastes in two-phase anaerobic digestion. Environ Technol 2005; 26: 329-40.

[31] Cadavid-Rodriguez LS, Horan N. Methane production and hydrolysis kinetics in the anaerobic degradation of wastewater screenings. Water Science and Technology 2013; 68: 413-8.

[32] Chen JL, Ortiz R, Steele TWJ, Stuckey DC. Toxicants inhibiting anaerobic digestion: A review. Biotechnol Adv 2014; 32: 1523-34.

[33] Cadavid-Rodriguez LS, Horan N. Reducing the environmental footprint of wastewater screenings through anaerobic digestion with resource recovery. Water and Environment Journal 2012; 26: 301-7.

[34] McCarty PL. Anaerobic waste treatment fundamentals. Public Works 1964; 95: 107-12.

[35] Plácido J, Zhang Y. Production of volatile fatty acids from slaughterhouse blood by mixed-culture fermentation. Biomass Conversion and Biorefinery 2018: 1-14.

[36] Plácido J, Zhang Y. Evaluation of esterification and membrane based solvent extraction as methods for the recovery of short chain volatile fatty acids from slaughterhouse blood anaerobic mixed fermentation. Waste and Biomass Valorization 2018; 9: 1767-77.

[37] Angelidaki I, Treu L, Tsapekos P, Luo G, Campanaro S, Wenzel H, et al. Biogas upgrading and utilization: Current status and perspectives. Biotechnol Adv 2018; 36: 452-66.

[38] Velásquez Piñas JA, Venturini OJ, Silva Lora EE, Calle Roalcaba OD. Technical assessment of mono-digestion and co-digestion systems for the production of biogas from anaerobic digestion in Brazil. Renewable Energy 2018; 117: 447-58.

[39] Velasquez O. Caracterizacion y análisis de la demanda de energía eléctrica en las ZNI del departamento de Nariño 2015.

[40] Castro L, Escalante H, Jaimes-Estéves J, Díaz L.J, Vecino K, Rojas G, Mantilla L. Low cost digester monitoring under realistic conditions: Rural use of biogas and digestate quality. Bioresource Technology 2017; 239:311-317.

[41] Rajendran K, Aslanzadeh S, Johansson F, Taherzadeh MJ. Experimental and economical evaluation of a novel biogas digester. Energy Conversion and Management 2013; 74: 183-91.

7 FIGURES AND TABLES LIST

Table 1. Physicochemical characterisation of FW and Inoculum.

Table 2. Economic analysis summary for Tumaco’s artisanal FW biogas production.

Figure 1. Cumulative methane production and methane production rate for different FW concentrations. (a) 1% TS, (b) 1.5% TS, (c) 2% TS and (d) 2.5% TS. The values are means ± standard deviations (vertical bars, n = 3rd deviations).

Figure 2. Duncan grouping for means of FW concentrations (alpha=0.05). Means covered by the same bar are not significantly different.

Figure 3. Ammonia production during anaerobic digestion of artisanal fish wastes at different TS concentrations.

Figure 4. Volatile Fatty Acids production during anaerobic digestion of artisanal fish wastes at different TS concentrations.

Table 1. Physicochemical characterisation of FW and Inoculum.

Parameter	**Fish waste**	**Methanogenic inoculum**
Moisture (%)	74,8	94,3
Total solids (TS) (%)	25,2	5,7
Volatile solids (VS) (%)	**88,9**	**84,9**
pH	7,4	7,7
COD (g/Kg) / (g/L)	265,0	93,59
C (%TS)	**50,59**	**41,6**
N (%TS)	**8,84**	**8,9**
C/N ratio	5,7	4,7
VFA (mg/Kg) / (mg/L)	1515,0	454,5
Ammonia (mg/Kg) / (mg/L)	627,2	487,2
Alkalinity (mg$CaCO_3$/Kg) / (mg$CaCO_3$/L)	650,0	1150,0

Table 2. Economic analysis summary for Tumaco's artisanal FW biogas production.

Tumaco's Artisanal fish landed per year	1131 tons
Tumaco's Artisanal FW per year (TAFWY)	509 tons
Potential biogas production from TAFWY	81,488 m^3 of biogas
Estimated energy production from TAFWY	489 MWh
Estimated thermal energy production from TAFWY	220 MWh
Estimated electric power from TAFWY	171 MWh

Figure 1. Cumulative methane production and methane production rate for different FW concentrations. (a) 1%

2% TS and (d) 2.5% TS. The values are means ± standard deviations (vertical bars, n = 3rd deviations).

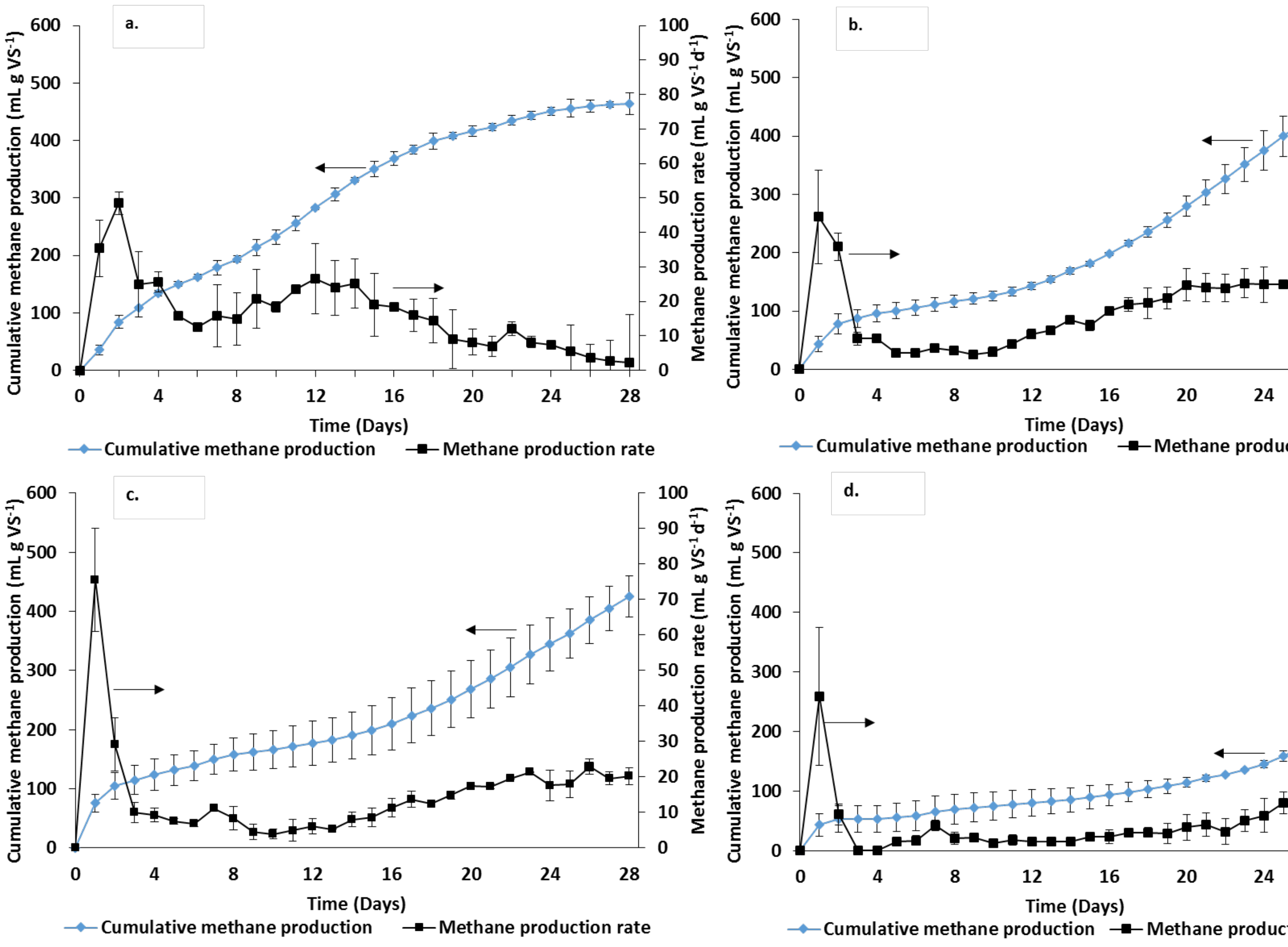


Figure 2. Duncan grouping for means of FW concentrations (alpha=0.05). Means covered by the same bar are not significantly different.

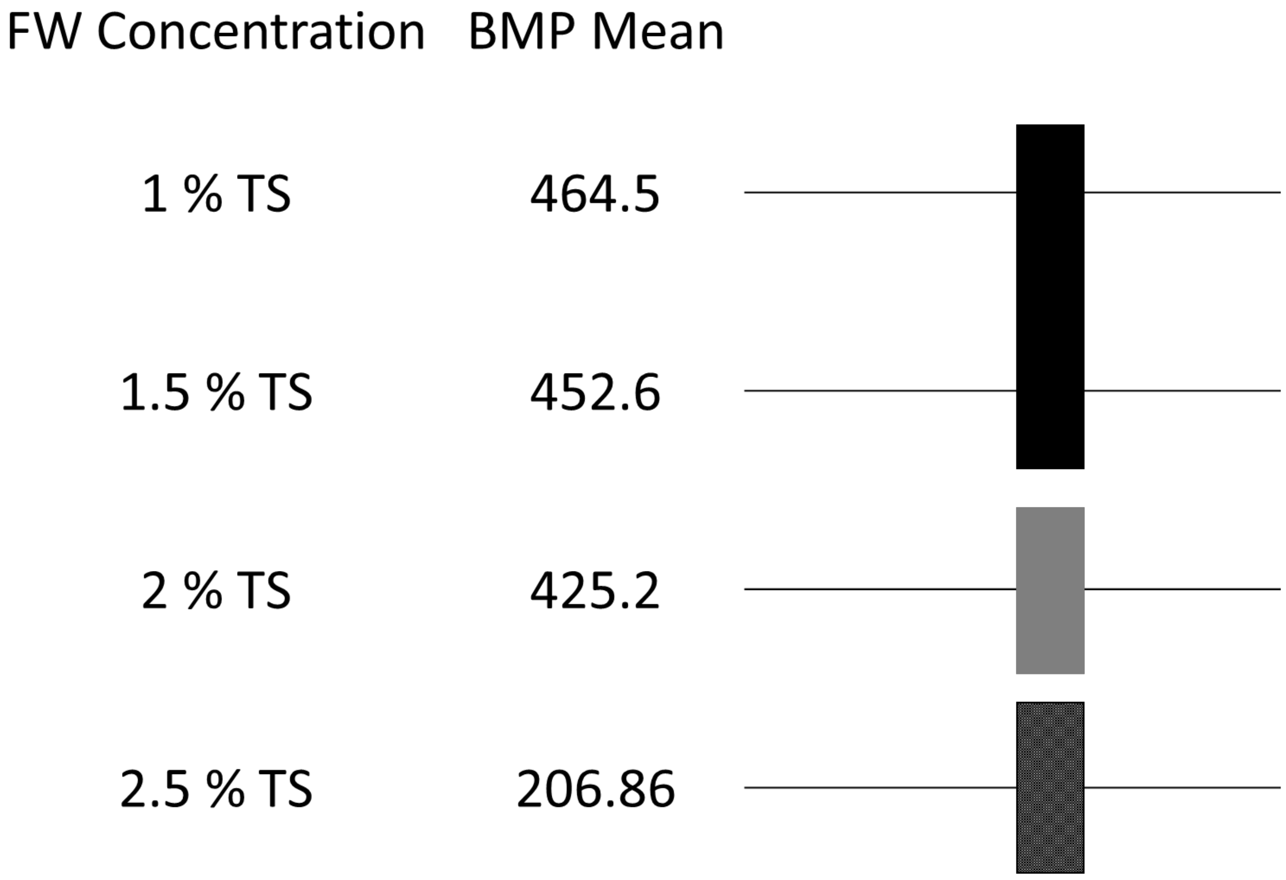


Figure 3. Ammonia production during anaerobic digestion of artisanal fish wastes at different TS concentrations.

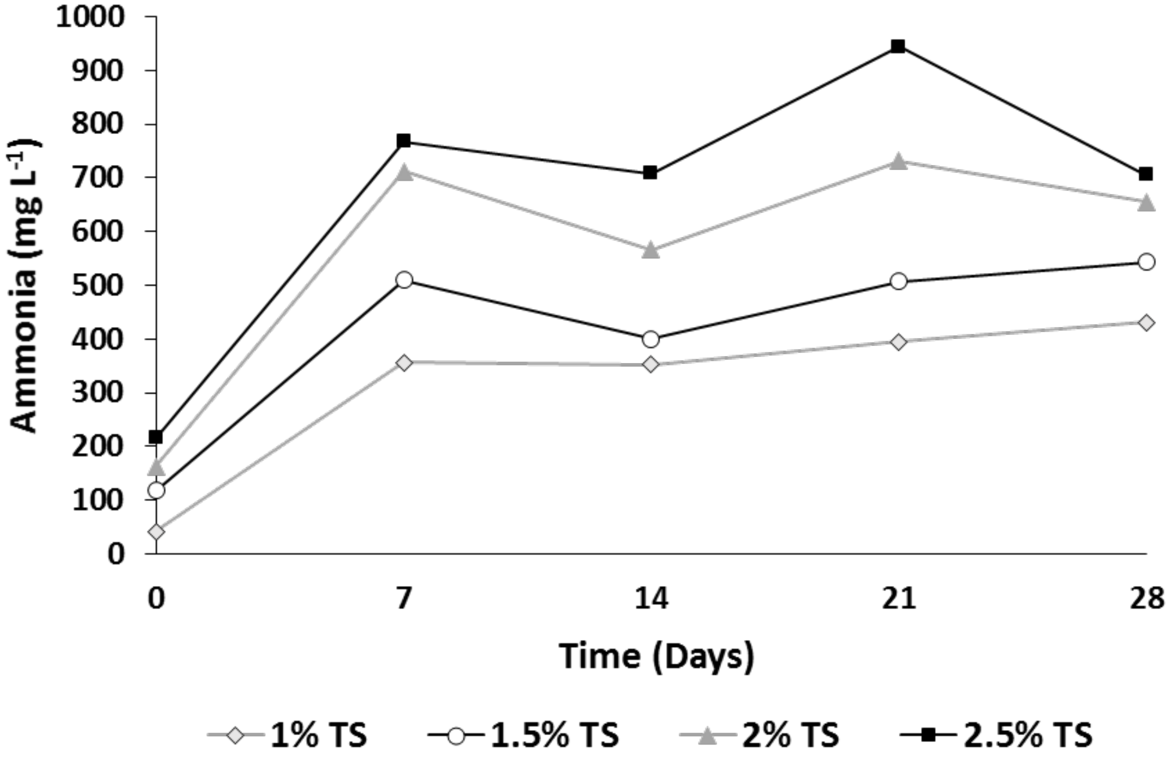
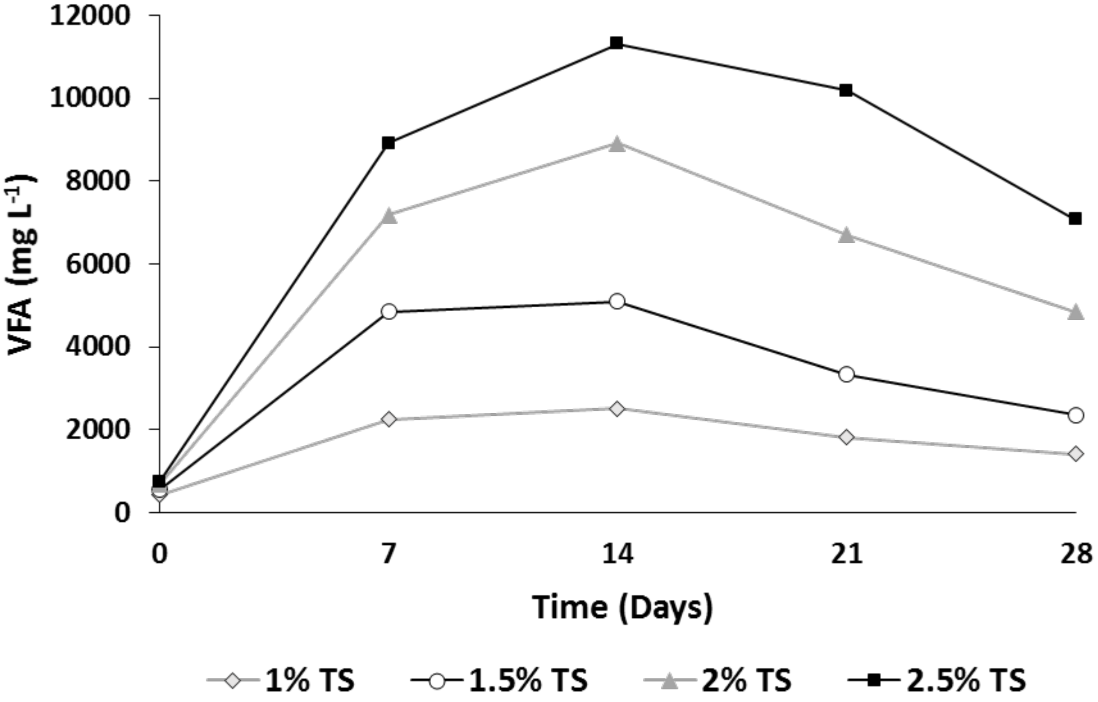


Figure 4. Volatile Fatty Acids production during anaerobic digestion of artisanal fish wastes at different TS concentrations



SUPPLEMENTARY MATERIAL

BIOMETHANE FROM FISH WASTE AS A SOURCE OF RENEWABLE ENERGY FOR ARTISANAL FISHING COMMUNITIES IN TUMACO, COLOMBIA

L.S. Cadavid-Rodríguez[2]*, M.A. Vargas-Muñoz[1], J. Plácido[2]

1. Departamento de Ingeniería, Facultad de Ingeniería y Administración, Universidad Nacional de Colombia, Carrera 32 No 12-00, Palmira, Colombia

2. Institute of Life Science, Swansea University Medical School, Swansea University, Swansea, SA2 8PP, Wales, UK

---

* Corresponding author.

E-mail address: lscadavidr@unal.edu.co

Phone: (57-2) 2868888 Ext: 35709

Annex 1

Statistical Analyses

Class Level Information		
Class	**Levels**	**Values**
tratam	4	1%TS 1.5%TS 2%TS 2.5%TS

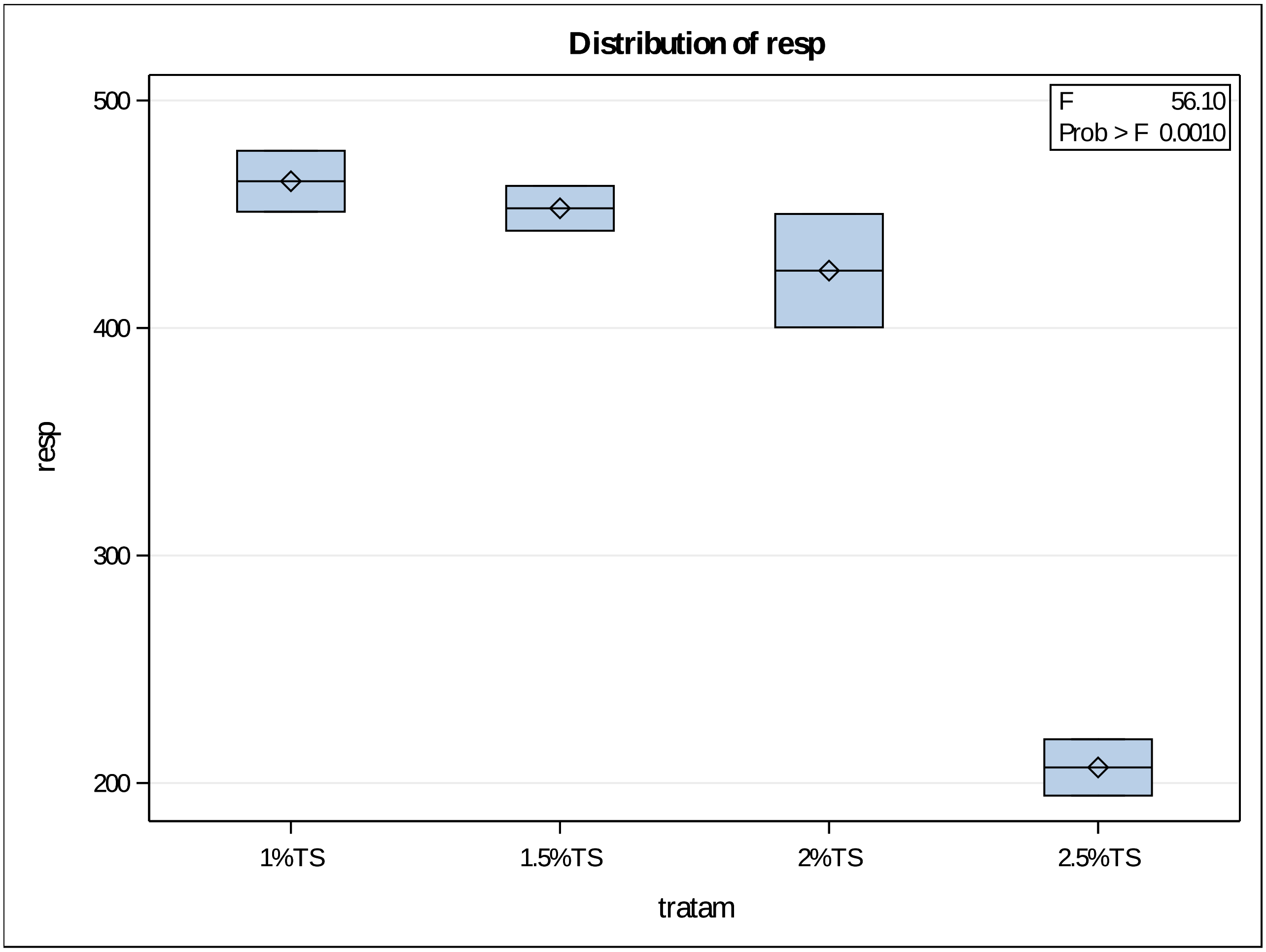
Number of Observations Read	8
Number of Observations Used	8

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	3	88445.60414	29481.86805	56.10	0.0010
Error	4	2101.95425	525.48856		
Corrected Total	7	90547.55839			

R-Square	Coeff Var	Root MSE	resp Mean
0.976786	5.918902	22.92354	387.2938

Source	DF	Type I SS	Mean Square	F Value	Pr > F
tratam	3	88445.60414	29481.86805	56.10	0.0010

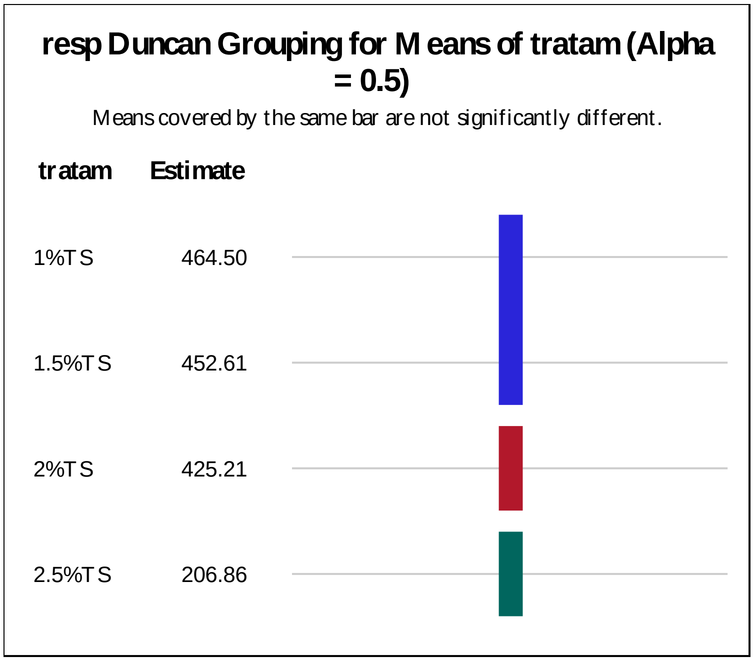
Source	DF	Type III SS	Mean Square	F Value	Pr > F
tratam	3	88445.60414	29481.86805	56.10	0.0010



Level of tratam	N	resp	
		Mean	Std Dev
1%TS	2	464.500000	18.9504617
1.5%TS	2	452.610000	13.9300036
2%TS	2	425.210000	35.2422020
2.5%TS	2	206.855000	17.5150350

Alpha	0.5
Error Degrees of Freedom	4
Error Mean Square	525.4886

Number of Means	**2**	**3**	**4**
Critical Range	16.98	17.19	17.06



resp Duncan Grouping for Means of tratam (Alpha = 0.5)

Means covered by the same bar are not significantly different.

tratam	**Estimate**
1%TS	464.50
1.5%TS	452.61
2%TS	425.21
2.5%TS	206.86

Moments			
N	8	**Sum Weights**	8
Mean	0	**Sum Observations**	0
Std Deviation	17.3285654	**Variance**	300.279179
Skewness	0	**Kurtosis**	-1.4714732
Uncorrected SS	2101.95425	**Corrected SS**	2101.95425
Coeff Variation	.	**Std Error Mean**	6.12657305

Basic Statistical Measures			
Location		**Variability**	
Mean	0	**Std Deviation**	17.32857
Median	-284E-16	**Variance**	300.27918
Mode	.	**Range**	49.84000
		Interquartile Range	25.78500

Tests for Location: Mu0=0				
Test	**Statistic**		**p Value**	
Student's t	**t**	0	**Pr > |t|**	1.0000
Sign	**M**	0	**Pr >= |M|**	1.0000
Signed Rank	**S**	0	**Pr >= |S|**	1.0000

Tests for Normality				
Test	**Statistic**		**p Value**	
Shapiro-Wilk	**W**	0.924541	**Pr < W**	0.4678
Kolmogorov-Smirnov	**D**	0.215127	**Pr > D**	>0.1500
Cramer-von Mises	**W-Sq**	0.070682	**Pr > W-Sq**	0.2435
Anderson-Darling	**A-Sq**	0.377664	**Pr > A-Sq**	>0.2500

Quantiles (Definition 5)	
Level	**Quantile**
100% Max	24.9200
99%	24.9200
95%	24.9200
90%	24.9200
75% Q3	12.8925
50% Median	-0.0000
25% Q1	-12.8925
10%	-24.9200
5%	-24.9200
1%	-24.9200
0% Min	-24.9200

Extreme Observations			
Lowest		**Highest**	
Value	**Obs**	**Value**	**Obs**
-24.920	5	-9.850	4
-13.400	2	9.850	3
-12.385	7	12.385	8
-9.850	4	13.400	1
9.850	3	24.920	6