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Social acceptance, emissions analysis and potential applications of paper-waste briquettes in Andean areas

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ABSTRACT

The research assessed waste-based briquettes consumption compared to conventional fuels in the Andes. Laboratory tests were conducted together with on-field analysis in Colquencha (Bolivia). The laboratory study shows that the performances of briquettes are better in terms of PM2.5 (933.4 ± 50.8 mg kg^{-1}) and CO emissions (22.89 ± 2.40 g kg^{-1}) compared to animal dung (6265.7 ± 1273.5 mgPM2.5 kg^{-1} and 48.10 ± 12.50 gCO kg^{-1}), although the boiling time increased due to the lower fuel consumption rate and firepower compared to shrubs. The social survey organized with 150 Bolivian citizens suggested that low-income households are not able to pay for an alternative fuel: about 40% would pay less than 4 USD per month, while methane use for cooking is positively correlated with the income level ($r = 0.244$, $p < 0.05$). On field analysis suggested that local cookstoves are not appropriate for briquettes combustion since indoor air pollution overcomes 30 ppm of CO and 10 mgPM2.5 m^{-3}. On balance, local small manufactures can be the main target for selling waste-based briquettes to reduce shrubs and wood consumption. However, briquettes production costs seem not yet competitive to natural easy-to-obtain fuels (i.e., animal dung). The research encourages the use of cellulosic and biomass waste-based briquettes in the Andean area for cooking, heating, or manufacturing and strongly advises policy-makers to introduce economic incentives for the recovery of secondary raw materials.

1. Introduction

Improving food cooking conditions in rural developing settlements is a research area with great impact (Akpalu et al., 2011; Gitau et al., 2019). The high consumption of firewood causes the degradation of natural resources and the threat of ecosystems (Liu et al., 2008). In rural Bolivia, the national institute of statistic underlined that, in 2012, firewood was the second most used fuel for cooking, counting for more than 45% of households that employ this type of biofuel in rural regions (INE, 2014). The use of alternative fuels to fossils and forest biomass is also important for those areas of the Andes where resources are very scarce and where climatic conditions are particularly extreme (Demirbas, 2008). Fossil fuel dependence of countries affects global health through increased climate change impacts, unpredictable fossil fuel markets, weak supply chains, and geopolitical conflicts (Romanello et al., 2022). Waste can play an important role in introducing alternative fuels instead of coal (Sagastume Gutiérrez et al., 2020), giving other valorization options as an alternative of waste open burning or dumping (Tatsuno et al., 2021).

Solid waste management (SWM) issues cost management, lack of technologies and know-how, low-standard final disposal options, among others, are also persistent in developing countries like Bolivia (Das et al., 2019; Bening et al., 2022). At the same time, Bolivian Andean areas suffer from the lack of energy sources, due to the climatic and geographic characteristics of the region (Salvador and Horn, 2021), increasing the dipendeence of the population to methane or alternative natural fuels like dung or shrubs. Waste valorization strategies can promote the business of secondary raw materials, reducing the waste inflow into final disposal sites and providing alternative source of energy (Moalem and Kerndrup, 2022). For example, the conversion of cellulosic and biomass waste into valuable fuels can be an alternative treatment process (Srivastava et al., 2014; Ifa et al., 2020), able to address both SWM and energy provision. Specifically, briquetting procedures can foster the application of non-recyclable biomass waste as a fuel (Chungcharoen and Srisang, 2020; Ferronato et al., 2022a).

Previous studies conducted in developing areas suggested that cardboard waste briquettes mixed with biomass waste (i.e., sawdust and

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Nomenclature

SWM	Solid waste management
LCV	Low calorific value
LEMS	Laboratory Emissions Monitoring System
HCV	High calorific value
WBT	Water boiling test
CCT	Controlled cooking test
IAP	Indoor air pollution

wood chips) have similar or better performances compared to firewood (Gado et al., 2014; Xiu et al., 2018). In addition, adding paper waste to other biomass fractions can improve the thermal efficiency compared to firewood, as well as fuel consumption (Lutaaya et al., 2023). For example, in Brazil, use of briquettes made of rice straw was suggested (Brand et al., 2017). Other studies underlined that the population in low-middle income countries are interested in using briquettes made of discarded materials to produce energy for heating and cooking (Fajfrlíková et al., 2020; Hu et al., 2020), while many experiments evaluated briquettes characteristics made of different waste sources (Lubwama and Yiga, 2017; Ajith et al., 2022). However, after the relevant publication of positive studies that advise to use briquettes in low-middle income settings, a question arise: "*why this type of fuel is still not widley used in rural and remote areas to substitute wood, coal, animal dung, among other fuels?*" The scientific literature lacks real world examples of waste-based briquettes application, linking technical characteristics and assessment to effective applications, as well as evaluation of population willingness to employ alternative fuels, taking into account local needs and economic issues. Simultaneously, applications of briquettes made of carboard waste are not reported in rural and developing Andean areas, although the region suffers from the lack of energy sources and poor waste management. Some factors can cause the limited use of this technology and energy source, discouraging its production and consumption.

The objective of the research conducted in Bolivia is to cover this literature gap, studing the use and the possible adoption of briquettes in Andean rural areas using biomass residues (sawdust from wood) and cellulose-based waste from the non-recyclable fractions obtained from cities located in the Andean plateau. The hypothesis behind the analysis is that cellulosic waste briquettes can be employed as alternative fuels in Andean areas for (i) cooking in domiciliary areas or (ii) for oven preheating in small manufacturing activities, contributing to solve waste open dumping and burning. The study would demonstrate with quantitative results this assumption. The reason behind the research is to reduce the use of fossil fuels and to boost the adoption of a more efficient fuel with low emissions rates, tackling, at the same time, the problem of solid waste final disposal. Therefore, the research assesses the population willingness to employ alternative fuels for cooking and heating (social surveys) and analyses carboard waste based briquettes in terms of energy consumption efficiency and quality of the final product with both a quantitative (laboratory tests) and qualitative approach (on-field studies).

Previous investigations conducted in Bolivia underlined how carboard waste briquettes made of 80% paper waste and 20% sawdust can reduce environmental impacts compared to coal, liquid propane gas, and wood in the whole life cycle (Ferronato et al., 2023). In addition, economically, waste based briquettes seems to have lower costs compared to coal, wood, and methane (if not subsidiezed), with potential better social benefits compared to the business-as-usual approach (Baltrocchi et al., 2023). However, a market analysis has not been carried out yet, and the social acceptance and practical use of briquettes in the field has not been assessed. The current research would contribute to fulfill this literature gap and provide evidence about the potential use and application of waste based briquettes in Andean rural areas.

2. Methods

2.1. Research methodology

The research was carried out in Bolivia. A rural setting has been selected as case study to evaluate the potential application of cellulosic waste briquettes. Briquettes are produced in the city of La Paz, about 100 km far from the study area. A development project supported the application of a briquetting machine to develop a market of alternative fuels in the Andes (Ferronato et al., 2022d). The analysis were organized within the same project framework. Three steps were followed:

- First, a social survey was organized through structured questionnaire surveys and face-to-face interviews. The outcomes of the analysis provide indications about the willingness of the population to buy and use an alternative fuel for cooking and heating. Results can give indication about future applications that briquettes might have in a rural context taking into account population behaviour, financial sustainability, and willingness to change habbits.
- Then, laboratory tests of briquettes and conventional biomass fuels typically employed by the population were carried out. The analysis aims to compare the combustion efficiency and the potential fuels emissions in a controlled setting. Findings will provide technical parameters to show whether waste-based briquettes can be considered better fuels compared to biomass and animal dung.
- Finally, following these studies, two on-field campaigns were organized. The first, to test briquettes use while cooking, the second to check the potential interest of manufacturing owners to employ briquettes instead of shrubs or wood for heating. Results can contribute to show real-world applications that briquettes can have, showing effective challenges and potential opportunities is alternative fuels consumption.

The results of the three steps were critically discussed to find the better use and potential market of waste based briquettes in the Andes.

2.2. Study area

The research took place in the urban area of Colquencha, Bolivia, at an average height of 4000 m a.s.l. The town is located in the Andean plateau, counting about 10,000 inhabitants, distributed in around 311 km^2. The main productive activities are agriculture, plaster production, and the use of clay for ceramics manufacturing. Potato is coultivated for local consumption and commercialization, while cattle and sheep are bred for the production of cheese, meat, wool and leather. The municipality of Colquencha does not have a home gas connection system, but receives a distribution of methane jars every two weeks. Gas seems to be one of the most widely used fuel for food cooking, followed by animal dung and firewood.

2.3. Questionnaire survey

The social survey was organized through face-to-face interviews conducted with structured questionnaires during public campaigns (Sewak et al., 2021; Kummer et al., 2022). The forms submitted to the population counts 24 questions related to the social characteristics of the respondents and their behaviour in energy consumption. Research questions and main answers are reported in Table S1. The survey took place in March 2022 in four days of field campaigns. Four people were involved to move around the area, talk to the population, and interview the citizens. The time and the people involved in the procedure were necessary due to the numerosity of households scattered in a wide area, not always present at home. So, two groups of interviewrs were organized and some households were visited two times. The questionnaire survey was dedicated to ten associations in the Colquencha municipality, in the four most important counties of the town. Therefore, citizens involved refer to women forming part the associations who were willing to be part of the survey. The sample was made mainly by women, who are the most active in cooking and fuel purchasing. Interviews were organized based on voluntary participation and were conducted door-to-door in the rural context. The sample size has been selected based on the number of people living in the area, making results representative of the rural context. The sample size was set to obtain 5% confidence interval (in case of binary response) at a 95% confidence level considering the whole community of Colquencha as reference. Globally, 150 citizens were interviewed. Questionnaires were anonimus and with generic questions, so no ethical approvals should be requested. Interviews took about 20 min each, based on a face-to-face interaction. Responses were correlated to find potential links able to explain some social patterns. A Pearson-correlation test was conducted for all answers provided. A correlation higher than ±0.3 was defined as a high correlation and was considered for further discussion: Only statistically significant correlations have been taken into account: A p-value minor than 0.05 is considered significant. The R-Studio v. 1.1.463 software was employed for the correlation analysis.

2.4. Laboratory assessment: combustion efficiency and emissions testing

The laboratory test aims to analyse the most important briquettes' combustion parameters and emissions in comparison with conventional fuels. Cellulosic waste briquettes, animal dung, shrubs and Taquia (Andean animal dung, made of coat and sheep manure) were assessed. First, the low calorific value (LCV) of each sample was analysed, followed by a combustion test (water boiling test - WBT) and emissions analysis in a controlled cookstove (Arora et al., 2014).

First, samples were prepared based on international standards EN 15443 – "Recovered solid fuels. Methods for the preparation of laboratory samples". The LCV is determined by secondary equations, knowing the high calorific value (HCV), humidity, volatile solids, and ash content, which are determined experimentally. The procedure and equations used for the determination of LCV are based on the EN 15400 – "Solid recovered fuels. Determination of calorific value", operating instruction manual for simple oxygen pump PARR 1341, and "NMX-AA-033-1985 municipal solid waste-determination of HCV". This method has been already employed in previous experiences conducted in La Paz, Bolivia (Ferronato et al., 2022b).

WBT was carried out to collect and compare five different parameters: Boiling time, thermal efficiency, burning rate, energy consumption, and firepower. A similar experiment was conducted to compare callulosic waste briquettes with firewood and 100% biomass briquettes (Ferronato et al., 2022c). Tests were conducted in triplicate. The analysis were evaluated at laboratory scale under controlled conditions. The same cookstove has been used for experiments to avoid adding other variables to the test. The procedure to determine the energy efficiency, emissions and the boiling procedure was based on the ISO 19867-1: 2018 standard in a Laboratory Emissions Monitoring System (LEMS). The LEMS collects and measures total emissions generated during the combustion phase. The CO and PM2.5 were monitored since represent the most important pollutants of indoor air quality, potentially affecting user health (González-Martín et al., 2021).

The values are collected in the acquisition system every 10 s. The captured emissions pass through a dilution tunnel where they are measured: in the case of CO, a sensor that contains an electrochemical cell is employed; an optical sensor and gravimetric methods were used for PM2.5 evaluation. The sample is collected in a cyclone through a fiberglass filter that is weighed before and after the test, and stored in a drier. The experiment was conducted during a high power phase. A maximum of 30 min were taken for each sample; if the boiling point is reached before 30 min, time and water temperature are recorded, otherwise the phase lasts 30 min. The pot contained 5L of water that was initially set at room temperature (20 °C) before starting the test. Before and at the end of each test, the mass of water, temperature, time, weight of fuel, and data necessary for the calculation of the energy efficiency and emissions were recorded.

Statistical analysis of the results obtained were conducted. The *t*-test to evaluate the statistical differences between means was employed to evaluate the statistical significance of each experiment. In particular, the parameters were tests to evaluate significant differences between briquettes and conventional fuels. A p-value minor than 0.05 was considered significant (95% confidence level). The R-Studio v. 1.1.463 software has been employed for the analysis.

2.5. On field analysis: materials, methods and settings

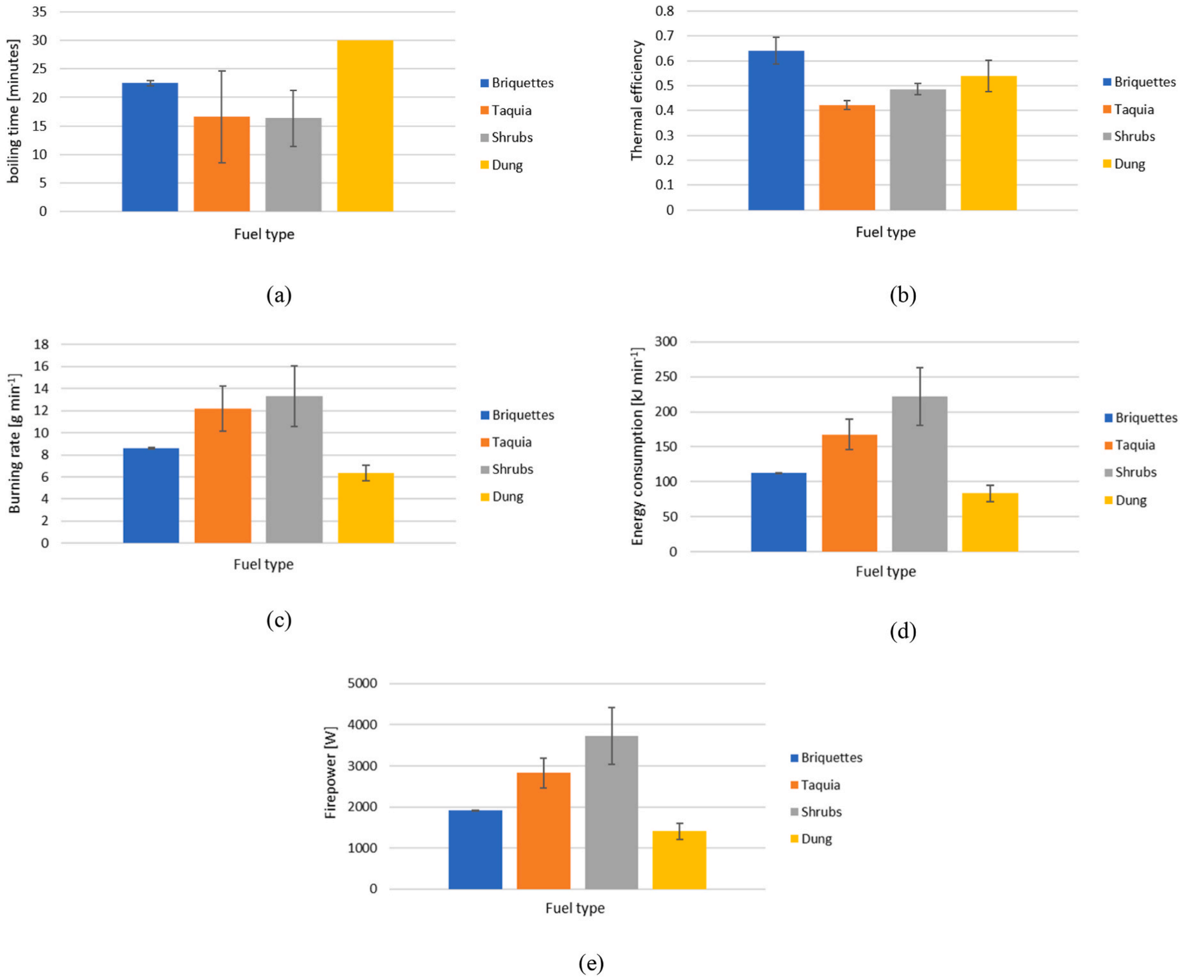
2.5.1. Cooking and water boiling tests at household level

From the social surveys, the women who were willing to be part of the field study were identified and involved. Due to the limited amount of time and fuel available for testing, and in agreement with the local community, two families were selected, giving their availability to test briquettes combustion. They were families that mostly use cow dung or brushes for cooking and that have an internal or external cookstove to prepare meals and to boil water. Tests were carried out in the traditional stoves made of clay, bricks, and a long iron bar to divide the stove burners (see Fig. 1S). In general, the method used for the field study is based on a simplification of the following tests: the Water Boiling Test (WBT) protocol combined with the Clean Cooking Test (CCT) protocol, and the Kitchen Performance Test (KPT), performing a food cooking process and simultaneously measuring fuel consumption and food processing times (Chomanika et al., 2022). Two tests with cellulosic waste briquettes were carried out in March 2022 and two tests with cow dung in the same period. Tests were used to:

i) compare the amount of fuel used when cooking and the time needed to prepare a meal;
ii) assess the power and the thermal efficiency of fuels on the field;
iii) verify the indoor air quality comparing the different fuels.

The CCT mainly analyzes how an improved kitchen acts compared to a common or traditional cooking method. The CCT was performed by cooking only one type of food in each case study (potatoes and vegetables). Traditional dry fuels (cow dung) were gathered for testing and briquettes were provided to the participating families. Each test was perform in the same way, although environmental conditions cannot be always considered comparable (external temperature is the most variable factor). Each meal has been weighed before testing to have a representative amount of food for each sample. Local environmental conditions were registered (humidity and temperature), while the fuel was weighed before and after cooking. Finally, the initial and final cooking time were monitored. Tests started with cold stoves and the fire was lighted in a "conventional" way when using fuels (it means that traditional fire lighting were employed).

Indoor air quality was monitored during the cooking phase. A portable equipment was employed: the Indoor Air Pollution Meter (IAP Meter) 5000 Series (available through Aprovecho Research Center) is a device that uses two sensors and other components to detect, monitor, and report on specific air pollutants like PM2.5 and CO and/or environmental factors such as temperature and humidity for measuring indoor air pollution (IAP) (MacCarty et al., 2010). The purpose of the IAP assessment equipment is to quantify the emissions by measuring concentrations of CO and PM2.5 in closed environments. These parameters are important to be monitored since long exposure to black carbon and PM2.5 can cause cardiovascular and respiratory disease (Zhu et al., 2023), while CO inalation might cause headache, weakness, nausea, vomiting, and, finally, loss of consciousness (Manisalidis et al., 2020). The air sample was measured every 10 s and concentrations were provided in ppm. The analysis was carried out in the two households for a



(a) (b) (c) (d) (e)

Fig. 1. Water boiling test conducted at laboratory scale: (a) Boiling time, (b) thermal efficiency, (c) burning rate, (d) energy consumption, and (e) firepower. Notes: boiling time of cow dung always exceeded the maximum time of analysis (30 min). Therefore, st.dev. is not reported.

total of four IAP profiles. Data were automatically stored on a memory card for later transfer to a computer. The equipment was placed approximately 1.3 m away from the stove and 1.3 m above the floor, as it mimics a typical cook's breathing location. The tests were carried out by installing the equipment in the fixed place. Data were collected before the cooking phase and during fuel combustion.

2.5.2. *Qualitative assessment of briquettes consumption in small manufacturing sites*

The pilot test for briquettes use as alternative fuels was carried out in the lime manufacturing sector. The plaster production process begins with the extraction of the raw material, which is limestone, similar to white marble, which is found in Vichaya, a small community near Colquencha. The plaster manufacture is handmade. Usaully, the facilities are precarious, and they are close to the raw material deposits to reduce transportation costs. After the kiln is assembled, the limestone is fired. After waiting a few days for it to cool down, local operators proceed to grind, bag, and sell the plaster.

Firewood, shrubs, cow dung, and Taquia are usually employed for pre-heating and heating the chambers. Field tests were carried out in traditional ovens for burning limestone to obtain plaster. The kilns are made by clay bricks with a hole in the middle, usually designed by the owners. Once the dimensions of the chamber and its capacity have been defined, steel joists are usually installed to support the load of limestone that is deposited in the oven, leaving a space for the combustion chamber.

In this context, two pilot tests were carried out in two different ovens. For the first pilot test, a kiln with a capacity to obtain 400 bags of plaster was chosen (1 bag of plaster is approximately 18 kg), while the second kiln had a capacity of about 300 bags. The tests were carried out in August and September 2022, for about 6h–10h out of 12h of burning time, typical period needed for plaster production. The first test aims to pre-assess the combustion system to evaluate the average amount of fuel employed for the production activity and to assess the appropriated pahses where brioquettes can be employed for heating. During the second test, briquettes were employed together with conventional fuels to qualitatively assess if the final product satisfied the owner.

The amount of briquettes inflow into the system and the biomass saved during the production phase were recorded. In both case studies, internal temperatures were monitored. A sensor was located at the bottom (soil), in the middle (oven), and in the upper side (plume) of the combustion chamber, to verify the maximum and minimum temperature achievable thanks to the fuels. These temperatures were qualitatively compared between fuels. In particular, attention was given to the temperature change during briquettes consumption.

Briquettes consumption was evaluated during the most appropriated phases to produce plaster. The experience of the owners was considered to use a specific fuel during the right time of the process. Plaster production is divided into two phases: the heating of the oven and the stones; firing the limestone so that the reaction with the temperature occurs and plaster is obtained. Briquettes were employed during the heating phase. The phase does not require the operators to be constantly feeding the combustion chamber with fuel and they can rest because the work to obtain gypsum starts in the night and they are exposed to low temperatures (below 0 °C); for the second phase, greater fuel power is needed, so traditional fuels were used. Research outcomes provide the amount of briquettes used and the conventional fuels (shrubs) replaced, taking into account the time saving. On the other hand, there would be economic savings or additiona expences due to briquettes consumption. Feedback from the owners was collected to assess the potential interest in using and purchasing briquettes.

3. Results

3.1. Social assessment and public acceptance

Around 97% of the people surveyed are women, all members of local associations. Only four men who are part of the same associations responded to the questionnaire. About half of the repondents (47%) are adult members (30–49 years old), while 15% are 19–29 years old citizens, and 37.5% > 50 years old. More than a quarter of females have a secondary level of education, 41% primary school education level, while 13% did not have an education degree. The results represent the three generations mentioned and show relatively that, in rural areas, there are still gaps in access to higher education. According to the results, about 87% of women have the responsibility of cooking in their family.

Almost 50% of the families interviewed have a gas stove and wood stove, which is mostly located outside their homes. In some cases, they have built covers to protect the stoves from rain. Globally, 61% of the citizens state that they use both types of stoves (wood stove and gas stove) and, among fuels, they use methane, dung, and firewood. Around 39% use exlusivelly gas stoves, while about 12% use exlusivelly wood or dung. Therefore, the vast majority use both cookstoves (up to 49%). Gas stoves are usually located in a single room (about 54%), while the wood stove is usually located outside the house. Therefore, the use of stoves still depends to the dry seasons and the moisture content of wood or dung.

The use of dung or firewood seems to be due to the costs of the methane and general habits: "*using firewood, food has more flavour. It is not the same as in a gas stove*". Up to 70% of the repondents stated that the fuel employed is due to the easy access, while only 4% state that it is for economic reasons. According to the data collected, dung is the second most used fuel for cooking since it is free of charge and easy to be collected. About 81% of women buy fuel, in other cases they collect it along the way, as is the case of dung and shrubs. The costs of purchasing fuel are between 0.3 USD to 5 USD per month, which is equivalent to a methane jar. Above 8–9 USD indicates the use of more than two methane jars for cooking per month.

About 37% of respondents do not know and do not answer about the amount of dung or firewood they use. The amount of dung or firewood is directly related to the daily use or what will be cooked once the stove is on. The amounts seem not so large and not effectivelly quantifiable from the survey: mostly between half jute to a sack (measures given by the participants and not measurable in mass). Every two weeks and every month the gas is purchased from the trucks that travel throughout the municipality, making it of easy access. Less than 45% of the respondetns stated that they would pay for an alternative fuel. In particular, 40% stated that they would pay less than 4 USD per month for obtaining fuels that allows replace dung or wood. However, women are aware about the pollution and health issues since only 30% stated that they do not experienced any problem, while 70% had respiratory disorders, eye irritations or similar pathologies. By the questionnaire, it can be possible to note that burning eyes and breathing complications can be caused by the use of dung and shrubs for cooking (Park et al., 2013; Xiao et al., 2015).

Results of the responses' correlation analysis are reported in Table 1. High and statistical significant correlations can provide valuable insights to comment on the social behaviour in fuel consumption and management. First, educational and economic level are positivelly correlated (r = 0.488, $p < 0.05$) although it is negatively correlated with

Table 1

Correlation analysis of the questionnaire survey. Correlations statistical significant ($p < 0.05$) are in bold. Underlined bold: strong correlation; Bold: correlation.

	1.2	1.4	1.5	1.6	1.7	1.8	2.1	2.2	2.3	2.4	2.5	2.6	2.7	2.8	2.9	2.10	2.11	2.12	3.1	3.2
1.4	**−0.426**																			
1.5	−0.079	0.022																		
1.6	**−0.276**	−0.049	0.139																	
1.7	−0.012	−0.099	0.021	**0.297**																
1.8	**−0.385**	**0.488**	**0.278**	−0.125	−0.113															
2.1	0.043	0.002	−0.098	−0.001	−0.003	−0.109														
2.2	0.118	−0.085	0.159	0.074	−0.020	−0.007	0.149													
2.3	−0.033	0.003	0.037	0.095	−0.003	0.050	**−0.251**	−0.065												
2.4	0.028	−0.079	−0.113	**0.216**	**0.175**	0.053	−0.040	−0.032	0.014											
2.5	0.071	0.034	0.063	−0.024	−0.015	−0.035	**0.165**	0.003	−0.066	−0.055										
2.6	0.122	0.031	−0.028	0.053	0.031	0.022	0.102	0.044	0.034	**0.437**	0.064									
2.7	−0.069	0.051	−0.157	−0.073	−0.132	0.055	**0.584**	0.099	**−0.183**	0.023	−0.055	0.146								
2.8	−0.056	−0.156	−0.007	0.086	0.132	0.142	**−0.504**	**−0.200**	**0.233**	0.121	**−0.167**	−0.058	**−0.427**							
2.9	0.149	−0.133	−0.116	−0.077	−0.085	−0.192	0.078	0.082	0.000	0.030	−0.062	**0.215**	0.057	−0.029						
2.10	0.029	**0.206**	−0.149	−0.024	−0.084	−0.205	**0.171**	−0.045	−0.159	0.005	0.089	**0.196**	**0.212**	**−0.261**	0.091					
2.11	0.042	**−0.209**	−0.128	−0.039	−0.048	0.184	−0.166	0.033	0.010	−0.141	−0.036	0.048	−0.028	−0.069	0.192	0.035				
2.12	0.091	−0.051	−0.140	**0.189**	**0.160**	−0.037	−0.031	0.047	0.008	**0.828**	−0.041	**0.443**	−0.063	0.068	0.101	0.033	−0.107			
3.1	0.070	**−0.250**	0.039	0.053	0.088	−0.005	−0.061	0.168	**0.178**	−0.024	−0.087	0.076	−0.141	0.101	0.113	**−0.236**	0.178	0.038		
3.2	−0.003	−0.080	−0.070	−0.008	0.039	**−0.248**	−0.078	0.026	0.019	0.095	−0.104	−0.007	0.019	0.107	0.051	0.080	**−0.207**	0.104	**0.190**	
3.3.	−0.067	−0.093	0.164	0.080	−0.020	−0.160	**0.244**	0.146	−0.101	0.059	0.167	0.007	0.219	−0.103	−0.115	0.006	−0.174	0.024	0.028	0.098

the age ($r = -0.385$, $p < 0.05$). It is due to the correlation between educational level and the age: younger ctizens have a higher education level ($r = -0.426$, $p < 0.05$), suggesting that the main economic issues are associated to the older part of the population. This affect the employment of different fuels for cooking. Results also show that households with a higher economic level prefer to emply methane for cooking ($r = 0.244$, $p < 0.05$). This might influence the use of advanced cookstoves. Indeed, households that employ methane for cooking also have access to gas cookstoves ($r = 0.584$, $p < 0.05$) and pay more for fuels, consuming higher quantities of methane per month ($r = 0.828$, $p < 0.05$). This also influence the cooking system. Finally, respondets that employ methane also locate cookstoves inside their home ($r = -0.427$, $p < 0.05$), while who employ animal dung or wood for cooking probably cook outside the house ($r = -0.504$, $p < 0.05$). Therefore, it seems that economic level considerably influence the fuel consumption behaviour and affect population health although it has not been clearly stated by the same respondents.

3.2. Laboratory analysis

Results of fuels LCV and characteristics are reported in Table 2. Research findings show that biomass and carboard briquettes have a higher LCV compared to cow dung, but lower than Taquia and Shrubs. In particular, ash content is considerably higher for animal dung, increasing the amount of particular matter that can be potentially emitted due to their combustion. On the other hand, briquettes and shrubs have a lower ash content.

Results of the WBT at laboratory scale are reported in Fig. 1. Research outcomes show that the boiling time is higher for cow dung and briquettes (22.7 ± 0.6 min). However, cow dung exceeds the maximum testing time for boiling water. Using dung, no boiling was recorded in 30 min, and the average maximum temperature achieved was 75 °C since dung presents high amounts of ash and high fuel consumption during the combustion phase. On the other hand, no differences between briquettes, Taquia (16.7 ± 8 min), and Shrubs (16.3 ± 4.9 min) combustion were found in a statistical point of view, showing that boiling time is extremely variable for shrubs and Taquia.

Fig. 1b shows that the thermal efficiency is higher for briquettes (64% ± 6). No statistical difference can be found compared to cow dung (54% ± 6). However, a statistical significance ($t_{[2]} = 4.41$, $p = 0.029^{*}$) can be detected compared to Shrubs (49% ± 2) and Taquia (42% ± 2) ($t_{[2]} = 6.27$, $p < 0.013^{*}$), underlying that briquettes are a better fuel compared to conventional ones. At the same time, briquettes' burning rate (Fig. 1c) is lower (8.57 ± 0.06 g min^{-1}) compared to Taquia (12.20 ± 2.03 g min^{-1}) and Shrubs (13.3 ± 2.75 g min^{-1}), although it is statistical significant only compared to shrubs ($t_{[2]} = 3.01$, $p = 0.012^{*}$) and cow dung (6.33 ± 0.71 g min^{-1}) ($t_{[2]} = 5.43$, $p = 0.031^{*}$). Similarly, energy consumption (Fig. 1d) is also different between fuels. In particular, it is statistically significant between briquettes (112.3 ± 0.6 kJ min^{-1}) and Taquia (167.7 ± 21.5 kJ min^{-1}) ($t_{[2]} = 4.45$, $p = 0.047^{*}$), as well as between briquetts and shrubs (221.3 ± 41.2 kJ min^{-1}) ($t_{[2]} = 4.58$, $p = 0.044^{*}$). Cow dung (83.7 ± 12 kJ min^{-1}) and briquettes can be compared. Finally, fire power (Fig. 1e) is statistically different between briquettes (1.91 ± 0.01 kW) and all fuels. Briquettes have a firepower lower than Taquia (2.82 ± 0.36 kW) ($t_{[2]} = 4.36$, $p = 0.049^{*}$) and shurbs (3.73 ± 0.69 kW) ($t_{[2]} = 4.55$, $p = 0.045^{*}$), although it is higher compared to cow dung (1.41 ± 0.20 kW) ($t_{[2]} = 4.32$, $p = 0.0496^{*}$), justifying the differences between the boiling time found during the test.

Results of the emission analysis are depicted in Fig. 2. The analysis underline that CO emission rate is lower for briquettes (22.89 ± 2.40 g kg^{-1}) compared to other fuels. In particular, the difference between Taquia (121.47 ± 0.33 g kg^{-1}) and briquettes is also validated by statistical tests ($t_{[2]} = 69.99$, $p < 0.001^{***}$), while differences between shrubs (112.99 ± 49.42 g kg^{-1}), and cow dung (48.10 ± 12.50 g kg^{-1}) seem not to have a statistical significance. In addition, briquettes combustion allows decreasing PM2.5 emissions (933.4 ± 50.8 mg kg^{-1}). It is particularly relevant if compared to animal manure: PM2.5 briquettes' emission rate is ten times lower than Taquia (14,071.3 ± 2493.5 mg kg^{-1}) ($t_{[2]} = 9.123$, $p = 0.0118^{*}$), and three times lower than cow dung (6265.7 ± 1273.5 mg kg^{-1}) ($t_{[2]} = 7.247$, $p < 0.0183^{*}$), while it is similar to shrubs (2130.3 ± 697.2 mg kg^{-1}).

3.3. On field research

3.3.1. Household briquettes consumption

During the field work, the results obtained at laboratory test were confirmed: cooking with briquettes need longer time and the power is lower compared to conventional biomass. It was observed that the boiling time was 31 min and 52 min for the two case studies examined, with a thermal efficiency of 5.2% and 4.8% in rural stoves, and a power of 0.29 kW and 0.48 kW. On the other hand, for Taquia combustion, it was observed that the boiling time was 28 min and 26 min, with a thermal efficiency of 4.7% and 5.4%, and a firepower of 0.62 kW and 0.67 kW. Therefore, making a comparison of the three parameters analysed (thermal efficiency, boiling time, and cooking power), it is found that the thermal efficiency of both fuels have a minimal difference and oscillates in the range of 4.6-5.4%, while the cooking power of animal dung is greater than briquettes. This also means that the consumption of Taquia is greater than briquettes: on average, 1.63 kg and 2.24 kg of briquettes, and about 2.28 kg and 2.16 kg of Taquia are consumed during the cooking phase. On the other hand, the cooking time rise using briquettes, which means longer time for women to cook an average meal (i.e., meat and vegetable soap): from 46 min with Taquia to 82 min with briquettes to prepare 40 potatoes and from 57 to 86 min to prepare 1L of soup.

Indoor air emissions during the cooking phase are reported in Fig. 3. The results highlight how briquettes generate higher IAP compared to cow dung during the tests carried out. Highest peaks are the result of a blackout in the combustion chamber, suggesting that the lighting phase is the most critical in terms of PM2.5 and CO emissions. It must be considered that results cannot be generilized since the analysis was collected in different moment of the day, with external variables that might affect the results. Hoewever, preliminary outcomes suggested that the use of an alternative fuel with higher combustion efficiency does not reduce IAP. Therefore, alternative cookstove or combustion chambers should be introduced together with alternative fuels.

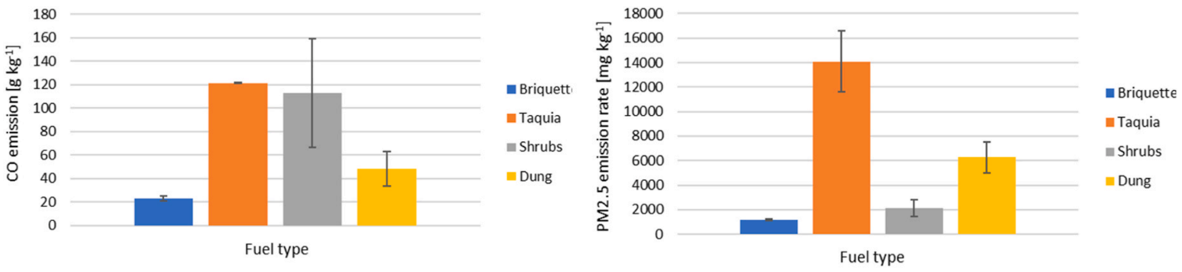
3.3.2. Briquettes use for lime production

Tests carried out allow calculating fuel consumption rate and plaster production time, together with temperature variations. Results of the trial are presented in Fig. 4. On balance, the fuel consumption rate was calculated of about 1.88 kg and 1.25 kg per minute, respectively during the first test, when no briquettes were used, and the second test, where briquettes were employed. Therefore, using briquettes, it is possible to

Table 2

Average values and standard deviation of HCV, LCV, moisture content, ash content and total volatile solids of the four fuels employed.

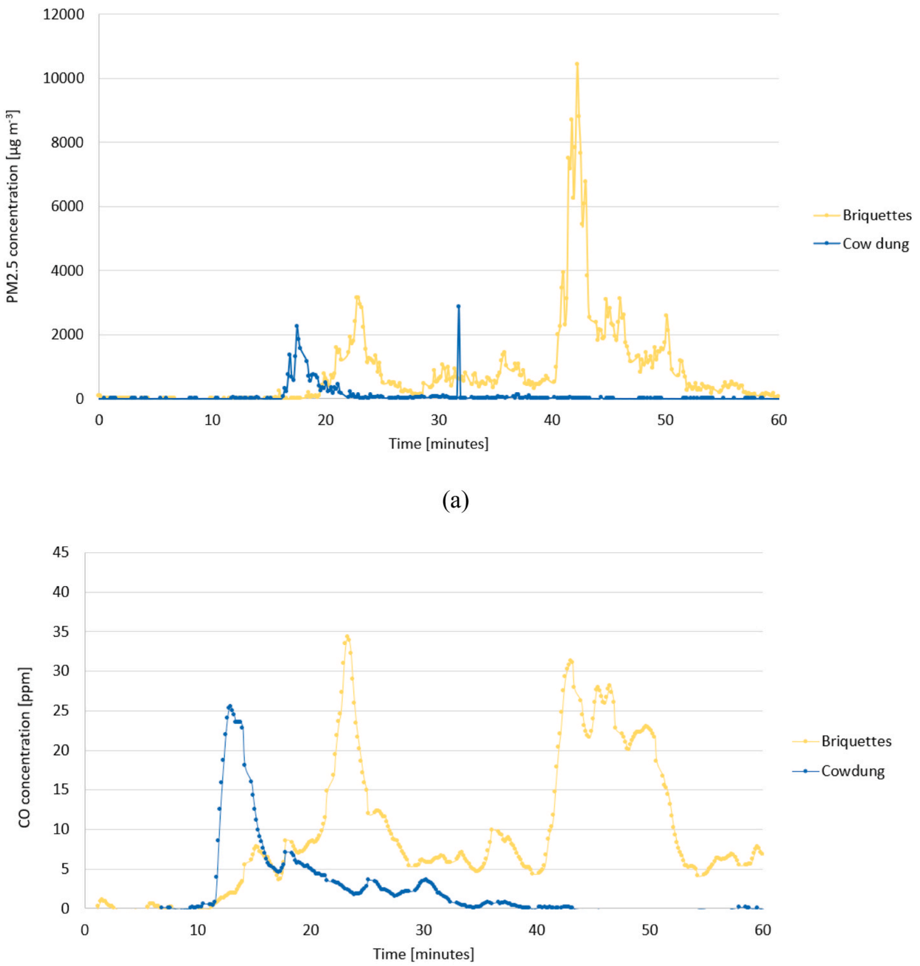
Parameters	Briquettes	St. Dev.	Cow dung	St. Dev.	Taquia	St. Dev.	Shrubs	St. Dev.
HCV (MJ kg^{-1})	15.63	±0.04	14.48	±0.38	16.00	±0.11	21.47	±1.45
LCV (MJ kg^{-1})	13.33	±0.04	12.61	±0.38	13.89	±0.11	14.77	±0.31
Moisture (%)	8.07	±0.42	9.23	±0.42	6.53	±0.28	5.68	±0.29
Ash (%)	11.97	±0.04	30.73	±1.71	19.4	±0.54	11.96	±0.17



(a)

(b)

Fig. 2. Emission rates per fuel: (a) gramms of carbon monoxide per kilogram of fuel and (b) milligrams of PM2.5 per kilogram of fuel.



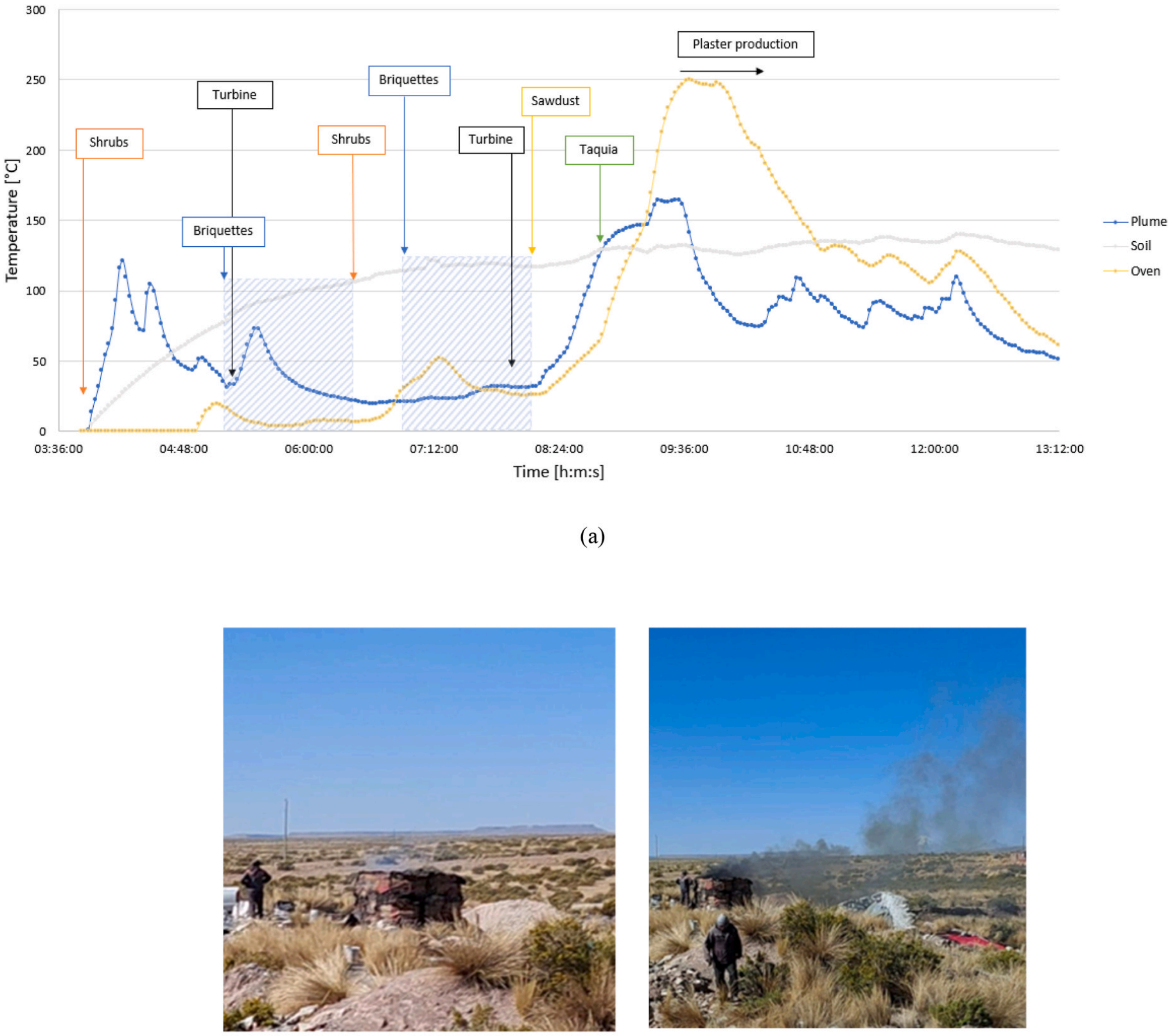
(a)

(b)

Fig. 3. Emissions analysis duering the cooking phase: (a) PM2.5 and (b) CO emissions (indoor concentration).

reduce the fuel consumption rate. About 282 kg of briquettes were spent during the pilot test, for a period of about 150 min. Briquettes retention time was equal to three additional hours, reducing the use of conventional fuels. In this way, fuel supply frequency was reduced, supporting operators to rest during the combustion phase. In particular, it has been estimated that the operator might have a rest time of about 4h per day if 30% briquettes are employed instead of cow dung or shrubs, thanks to the briquettes' higher combustion efficiency.

However, the briquettes' power is lower compared to traditional fuels, explaining why briquettes cannot completely replace traditional fuels. Therefore, it can be stated that the use of briquettes reduces emissions during a limited period of time. As seen in the graph reported in Fig. 4a, briquettes are employed during the first phase (chamber preheating) and for two limited period of time (about 3 h). During this phase, air emissions are lower, as also qualitatively visible in Fig. 4b compared to Fig. 4c. These data were obtained from the test that was carried out in an oven with a capacity to obtain about 6 tonnes of plaster per day (daily revenues of about 720 USD), and that usually employ around 30 bales of shrubs (about 20 kg per bale) mixed with animal dung and sawdust. When carrying out the test, the use of natural



(a)

(b)

(c)

Fig. 4. Analysis of briquettes combustion in manufacturing sites: (a) Temperature variation during the combustion phase in plaster ovens, plume and soil; qualitative evaluation of (b) gas emissions during briquettes and (c) shrubs combustion.

biomass (shrubs) was reduced from 30 to 20 bales, saving about 250 kg of shrubs. One bale of shrub costs about 2 USD (0.1 USD kg^{-1}). Similarly, during this period of time, wood can be used for fueling (about 200 kg) since shrubs are not always available during the rainy season. Therefore, the costs saved can be of about 25 USD when shrubs are used or 114 USD (0.57 USD kg^{-1}) when wood is employed during the rainy season. The amount of briquettes employed for replacing this amount of shrubs or wood is of about 90–147 USD (0.32-0.52 USD per kg). Therefore, shrubs are always cheaper than briquettes, but the replacement of wood with briquetes can be profitable during the rainy season if the cost of briquettes is reduced and compensated by national or local incentives.

4. Discussion

4.1. Limitation of the analysis and upcoming research

The research introduced both laboratory tests and preliminary on-field surveys to evaluate briquettes combustion and consumption in low-income settings. However, on field analysis are difficult to be organized and managed due to the unpredictable behaviour of the local population, the distances from urbanized areas, the period of the day when production or cooking activities are carried out, among other random factors. This affects the number of samples to be collected and the statistical significance of the results. For this reason, the outcomes of this on-field research cannot provide average results and standard deviation, neither confidence levels or statistical evaluations. In addition, CCT and WBT are very difficult to be assessed on the field. Emissions analysis are very variable due to the change in environmental conditions and the location where cookstoves are placed are not always optimal for testing IAP.

In general, more samples and analysis should be conducted aiming at collecting more data and providing statistically relevant results (Poupard et al., 2005). Maybe, fees to be payed to the participants or providing economic prizes in a certain period of time can incentivize the participation of the local population (Hoffman and High-Pippert, 2010), therefore involving higher investments and time to conduct the analysis. This is a difficult practice to be carried out in the context but it is really necessary to better evaluate the market and to identify the real potentialities of waste-based briquettes as alternative fuels in Andean areas. The research provided preliminary results to set the way to go for evaluating the market of waste based briquettes in the Andes.

4.2. Future developments for briquettes production and consumption in andean areas

The responsibility for food preparation, cooking, and fuel purchase is of women, who alternate the use of various cooking fuels depending on climatic factors (rainy or dry season) and with the purpose to minimize costs (purhcase of methane is costly for families). Households, in almost half of the cases, have gas stoves and cookstoves that are usually located outside their houses. In some cases, they have built covers so that the rain does not get fuels and cookstoves wet, and the stove can be used during the rainy season. In other cases, they are without covers, making cooking a real challenge during the same season. The young population (with high education level) can be an important actor for introducing alternative fules in the Andes since they are aware of the problems related to IAP and combustion efficiency. However, the research clearly shown that, at household level, briquettes cannot be effectively employed for three main reasons:

1. Low-income households use wood, shrubs, and Taquia since it is free of charge and easy to be collected. Therefore, families are not conveyed to buy an alternative fuel to minimize pollution and maximize cooking efficiencies.
2. Middle-income households are more likely to buy methane since they already have an improved cookstove for cooking. They are not interested in paying for an alternative fuel like briquettes, which has lower performances compared to methane.
3. Cookstoves are not appropriate for burning briquettes. In the current situation, the higher thermal efficiency of briquettes are lost due to the lower stoves performance, making briquettes not so attractive for the market.

On balance, the priority should be given to improved cookstoves, maybe with external chimneys that can reduce IAP (Bruce et al., 2004). In addition, when possible, methane can be fostered to mitigate the IAP, following by electric stoves in a long-term period.

On the other hand, the research underlines the potential application of briquettes for plaster production. It allows to:

- Mitigate the amount of shrubs and wood to be collected and burned during the combustion phase;
- Reduce the working time that the operators should spend during the night to feed the combustion chamber with shrubs and Taquia;
- Reduce emissions, and environmental impacts.

Therefore, briquettes production and consumption for manufacturing purposes, like the case of plaster production, can be an interesting future application of waste-based briquettes. Manufacturing needs high amounts of fuels to be daily employed and lime production activities contribute to wood consumption and pollution generation due to low comsbution efficiencies. In this scenario, briquettes consumption can be more advantageous thanks to their higher thermal efficiency, despite their lower fire power. Therefore, future applications of waste based briquettes should follow this direction although more research and analysis should be carried out regarding general expenses and management costs. This is the challenging part that may cause the failure of briquettes commercialization in the Andean area.

4.3. *Briquettes consumption: reasons of failures and real applications*

The research provided preliminary results that underline how briquettes production seems to be too expansive for its commercialization in Andean areas or low-middle income settings. The production costs are higher compared to natural biomass, suggesting that it should be covered by other sources: waste procuders should pay a tipping fee (Tanoh et al., 2022) to valorise the waste and to cover the cost of the whole SWM system (Alzamora and Barros, 2020). This can halve briquettes' market cost, making them interesting for manufacturing or cooking in the Andes. Indeed, briquettes can be interesting during the rainy season for:

- Households, to obtain an alternative fuel instead of animal dung, wood or shrubs;
- Manufactures, replacing firewood to reduce the working time of operators that should costantly feed combustion chumbers during the night period for oven pre-heating.

Several studies underlined how briquettes are better compared to conventional fuels (Dinesha et al., 2019) since they can be obtained from different sources (Mendoza Martinez et al., 2019). It is also underlined how waste densification is a low-tech solution to tackle both scarsity of energy resources and solid waste open dumping (Bajwa et al., 2018; Silva et al., 2022).

So, why waste-based briquettes are not employed in the vast majority of low-middle income and isolated areas? Also the current research underlined how, at laboratory scale, briquettes have higher combustion efficiencies and reduced emissions compared to animal dung, shrubs, and natural resources. However, the research conducted in Colquencha provided some additional indications about the reason why briquettes might not be considered the best fuel for these contexts:

- Briquettes production represesants a low-tech technology that needs time for its implementation and economic resources, as well as technologies and know-how. It can be trasleted into investments and expenses that need to be covered. Therefore, briquettes should have a market price. However, it cannot be afforded and sustained by the beneficiaries that can be interested on it, such as low-income households and small-scale manifactures.
- Briquettes are usually suggested for cooking purposes. For sure they can be employed instead of wood and shrubs. However, their benefit can be reduced due to the low-tech cooktoves where combustion take place, enlarging the cooking period and causing the same IAP as conventional fuels.

On balance, economic issues and real-world applications are the main barriers to generate a market in low-income settings where natural resources are available for free. If briquettes made of waste would be introduced to a developing market (high-income households might not be interested on it), these problems should be taken into account. Strategies and policies like (i) the introduction of improved cookstoves, and (ii) incentives to briquettes production and consumption can be introduced. This can make waste-based briquettes attractive for potential investments from the private sector. If supporting policies are not introduced, the production and consumption of briquettes seems to be destined to fail in developing areas, reducing the impacts of future research working on this direction.

5. Conclusions

Laboratory tests proved that cellulosic-waste based briquettes are better fuels compared to animal dung and shrubs, which are conventional fuels used in the Andes. Thermal efficiency of briquettes achieved 64% $\pm$ 6, with a burning rate equal to about 8.57 ± 0.06 g min^{-1}. At the same time, briquettes show an emission rate of about 22.89 ± 2.40 gCO kg^{-1} and PM2.5 emissions of 933.4 ± 50.8 mgPM2.5 kg^{-1}, lower compared to conventional fuels. However, for domestic purposes, the problem is related to the low-tech cookstove employed in rural areas. The combination of laboratory analysis with field research allows giving interesting outcomes about the real applicability of briquettes: Traditional cookstoves reduce the thermal efficiency and the better performance of briquettes. Therefore, for spreading the use of alternative densified fuels, improved cookstoves can be introduced. On the other hand, the employment of briquettes for manufacturing seems to be promising: The high thermal efficiency of briquettes allows reducing the working time of manufacturing operators for about 4h per day, reducing the emissions and the consumption of conventional fuels. On balance, barriers are related to:

- higher costs compared to natural biomass (in many cases, available for free);
- longer time needed for cooking;
- IAP increased by low-tech cookstoves.

This can make difficult the diffusion of briquettes for cooking. In addition, andean population is not used to employ fuels for heating. The study suggested that the great potentiality arise to the local manufacturing actvity, proposing waste based briquettes to be employed for pre-heating combustion chambers. However, briquettes cannot be used to substitute 100% of conventional fuels (natural or fossil) and the costs seem to be too high if briquettes are not subsidised or if briquettes' production costs are not covered by waste producers. Pilot analysis show that briquettes can be employed for reducing about 30% of conventional fuels (animal dung and shrubs), although with a potential increase of costs of about 3–5 times if compared to shrubs: on balance, the potentiality exist, but waste-based briquettes, to date, seem to be too expensive compared to natural fuels, although they can be employed during the rainy season instead of wood. New strategies should be put in place to support and encourage briquettes production and consumption. The dissemination of improved cookstoves among low-income households, economic incentives for briquettes production, and the introduction of effective waste management fees that can cover biomass waste management and transformation costs can overcome these barriers.

In conclusion, the research encourages the employment of cellulosic and biomass waste based briquettes in the Andean area for cooking, heating, or manufacturing. This strategy can reduce the consumption of wood and shrubs for heating, and the waste inflow into sanitary landfills, mitigating green-house gas emissions and increasing carbon sequestration. This can be another contribution to fight against the climate change crisis and to make low-middle income countries more resilient in the short term. At the same time, research outcomes call policy-makers to action, establishing incentives for the recovery of secondary raw materials. At the same time, waste-producers should be aware that they must fully cover waste collection and treatment fees to support the appropriate management of discarded resources: this is the most challenging task in the low-middle income world.

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Authors' contribution

All authors contributed to the study conception and design. Data collection was in charge of Iris Jabneel Calle Mendoza. The data analysis was carried out by Iris Jabneel Calle Mendoza, Marcelo Antonio Gorritty Portillo and Navarro Ferronato. Field and laboratory work was in charge of Iris Jabneel Calle Mendoza, Jazmin Gidari Ruiz Mayta and Jose Luis Alanoca Limachi. The first draft of the manuscript was written by Navarro Ferronato, and all authors commented on earlier versions of the manuscript. All authors read and approved the final manuscript.

Ethical approval

Not applicable.

Consent to participate

Not applicable.

Consent to publish

Not applicable.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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Appendix A. Supplementary data

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