

Cereal Straw Production Analysis, Availability of Materials, and Provincial Map for Manufacturing of Sustainable Prefabricated Panels

Carlos Cobrerros,^a Domingo Espinosa,^b Francisco Hidalgo,^b A. Manzano-Ramírez,^c and José Luis Reyes^{d,*}

Throughout history, energy consumption and the demand for resources have gradually increased. The construction industry, by direct or indirect actions, consumes over 50% of the energy produced, is responsible for 30% of the CO₂ emissions, and consumes more raw material than any other industrial activity. Architecture alone cannot solve global environmental problems, but it can contribute significantly. A high recyclability rate can be achieved through the management of renewable natural materials or waste. The application of prefabricated building systems can be an economical solution, saving energy and reducing waste. This work presents the prefabricated compressed straw panel as part of a paradigm shift toward sustainable architecture, which offers the opportunity to use new materials and construction systems but takes local and specific circumstances into account. The density of cereal straw for use in prefabricated compressed straw panel production in Badajoz, Spain was also studied.

Keywords: Cereal straw; Straw panel; Sustainable architecture

Contact information: a: Facultad de Ingeniería, Universidad Autónoma de Querétaro, Av. Cerro de las Campanas s/n. Colonia Las Campanas, C.P. 76010, Santiago de Querétaro, Qro., México; b: C/ Miguel Angel Asturias S/N, Módulo 5. C.P. 41950, Castilleja de la Cuesta, Sevilla, España; c: CINVESTAV-Querétaro. Libramiento Norponiente # 2000, C. P. 76230, Fraccionamiento Real de Juriquilla. Querétaro, Qro. México; d: Facultad de Ingeniería, Universidad Autónoma de Querétaro, Av. Cerro de las Campanas s/n. Colonia Las Campanas, C.P. 76010, Santiago de Querétaro, Qro., México;

* Corresponding author: araiza@uaq.edu.mx

INTRODUCTION

Human life revolves around constructed habitats, making the construction industry is one of the largest and most active growth sectors worldwide. The construction industry, by direct or indirect actions, consumes over 50% of the global produced energy (Edwards 2008), is responsible for 30% of CO₂ emissions, and consumes more raw material than any other industrial activity (about 3,000 Mt/year, almost 50% of overall consumption) (Pacheco-Torgal and Jalali 2012). The negative environmental impact of the construction industry is defined by its consumption of non-renewable resources and waste generation involving pollutants (Wadel *et al.* 2010). Additionally, the increasing population and growing requirements for buildings and infrastructure will continue to elevate resource consumption and waste generation (Pacheco-Torgal and Jalali 2012).

The use of nonlocal materials influences energy costs due to their transportation (Berge 2001). Currently, the construction industry has not paid sufficient attention to renewable, natural, and local construction products or materials. A sustainable building should opt for solutions that include using renewable energy, taking advantage of energy

efficiency and the material's embodied energy, using natural materials from renewable, local, or recycled resources, controlling the CO₂ produced during construction, recycling waste, and collecting and reusing water.

The present research assesses the technical and economic possibilities of the construction industry to improve manufacturing processes and on-site applications. It thus advocates construction sector specialization and industrialization based on prefabricated or industrial components (Pich-Aguilera *et al.* 2008). There have been international studies that concluded that these industrial systems have to reduce costs, time, and labor (Ahmad Bari *et al.* 2012), to reduce resource consumption, to improve construction quality, and to reduce CO₂ emissions resulting from manufacturing and transportation logistics during construction and in the building life cycle (Wadel *et al.* 2010).

Until now, industrialization has been linked to the manufacturing processes of steel, aluminum, concrete, and plastic materials (Segre 2008). There are researchers who suggest a paradigm change in response to what the local environment offers. The market currently offers standardized or industrialized construction solutions. However, except for the case of wood, there has been little progress in studies concerning industrial or standard systems based on lignocellulosic plant fibers, including cereal straw.

Agricultural lignocellulosic fiber can play an important role as an alternative to the use of forest vegetable fiber (FAO 2004). It is an organic, natural raw material available at a very low cost, from a local environment, and it has a low environmental impact, resulting in low CO₂ emissions and energy costs. It can replace and even improve the quality of conventional materials.

The use of by-products, such as cereal straw, can be attractive from the standpoint of the environmental, whenever it does not compromise soil conservation (Bowyer and Stockmann 2001). A lot of agricultural waste is generated in developing countries, due to the growth and modernization of industries based on agricultural production. Currently, many of these agricultural residues are burned or deposited in the soil, which can cause several environmental problems such as air pollution, greenhouse gases emission, and the occupation of useful land (Karade 2010). Biodegradation of lignocellulosic residues in a field emits methane, a greenhouse gas that has an effect 72 times stronger than CO₂ (Leliveld and Crutzen 1992) and composting or burning some wastes is not permitted by law (Karade 2010). This makes finding alternative methods of disposal for these agricultural residues very important.

Cereal Straw, Agricultural By-product

By-products of plant fibers from farms are used in order to achieve a high recyclability rate, attempting to approach the maximum usable amount of natural capital. Cereal straw is a low-cost, abundant, and renewable lignocellulosic material (Savastano *et al.* 2003). In developing countries, the growth of agro-forest-based products industries has accelerated the generation of waste like rice husk, wheat straw, barley straw, bagasse, palm oil, hazelnut, and sawdust (Karade 2010). Globally, there is a high production of cereal crops, especially wheat, barley, and corn, with straw as the most known and used by-product (Bowyer and Stockmann 2001).

Straw can be defined as the fibrous stalk of a cereal plant (Mahlke and Minke 2005). After harvesting the grain, a large amount of straw is generated as a residue (Karade 2010). It has been reported that cereal straw has a more complicated micro-structure than wood fiber, with a great variety of cell size and cell types. Cereal straw

contains 45% cellulose (much like timber), 28% hemicelluloses, and 18% lignin (Halvarsson *et al.* 2004).

Straw has been used in construction since antiquity, in roof solutions, as fibrous reinforcement in adobe, in lightened earth blocks, in continuous earth walls, *etc.* Today, there are new ways of using these fibers which, thanks to their homogenization, are viable in the demanding construction market. Agro-industrial waste can make a vital contribution to the construction industry without compromising the durability and comfort standards of buildings (Mathur 2005). For example, there are studies on the use of wheat straw bales (Minke and Mahlke 2005). There is an innovative prefabricated straw bale-building system, the "ModCell" system, consisting of straw bale and wooden frames, where straw bales are compacted, reinforced, and protected.

There are also studies of fiber and particle composite panels, in which the cereal straw is the main component in the compound, the single base component of the panel, and/or added reinforcement in the matrix or binder (Youngquist *et al.* 1996). The panel or board has small particles of cereal straw immersed into organic or inorganic binders (Stulz and Mukerji 1993), which are consolidated with heat and pressure (making panels of low, medium, and high density).

In general, cereal straw particle- or fiberboards tend to be somewhat poorer in quality than those made of wood. This type of panel goes through a manufacturing process that has extra energy costs. Energy is expended in the production of resins, cutting of the particles, in the mixture with the resin, as well as in the compression and drying process (Woolley *et al.* 1997). In most cases, the use of water and especially the problems arising from the use of formaldehyde or synthetic resins as binders are greater than in the case of wood fibers (Wooley *et al.* 1997).

Nevertheless, there are prefabricated compressed straw panels for architectural applications that do not use formaldehyde in the compaction process (Mosesson 1980). These kinds of panels, which are taken as the reference for the analysis of production and availability of straw, are manufactured by applying heat and pressure extrusion and melting the straw fibers to release their own resin (lignin) without extra binders, creating a structural panel with good performance that achieves a high strength-to-weight ratio. Without protection, such panels are suitable only for indoor use because of their low durability.

Availability of Cereal Straw

It is assumed that cereal straw, despite having other purposes, is produced in such large amounts that its availability is sufficient to assure the production of compressed straw panels.

It is difficult to ensure consistency of the cereal straw and impossible to prevent putrefaction of straw that remains wet for a long period of time. Cereal straw has the disadvantage of being unsuitable for economic transport and storage. By contrast, the environmental impact of the production of straw is very low. After solving the above-mentioned problems, wheat cereal straw can be considered an excellent resource and raw material for construction material applications.

This work discusses whether existing agricultural production in Badajoz (Spain) is sufficient for the development of a prefabricated building material and components manufacturing plant.

PRODUCTION, MATERIALS AVAILABILITY, AND PROVINCIAL MAP

Scope

In this work cereal straw (preferably wheat) was chosen as the raw material, based on consideration of the technical requirements of the end product and the agricultural activities of the province. Next, a methodology was applied to quantitatively measure the potential for acquisition of cereal straw acquisition within the province of Badajoz.

The agricultural districts (comarcas) were chosen as boundaries to compare different areas because they are the administrative divisions for the management of raw materials. However, this study also included an analysis at the municipal level. Finally, assessment and interpretation of the results were carried out.

Methodology

The first step in the analysis was to establish the necessary criteria for a viable straw panels manufacturing plant. According to the report by FIVECO (2011), 4080 tons of straw per year are needed to produce enough panels such that a manufacturing plant can be regarded as feasible. Regardless of physical factors or access to infrastructure, the key factor for the location is the availability of raw materials.

To determine the supply of cereal straw in the province of Badajoz, the latest available statistical and cartographic data from the Ministry of Environment and Rural Environs and Marine of the Government of Spain and the Ministry of agriculture and Rural Development of Extremadura were taken into account. This information was processed by a computer using geographic information systems (GIS)¹ so that it could be represented and analyzed cartographically. Likewise, the administrative boundaries of the agricultural districts and municipalities were included in the digital GIS maps, so that statistical analyses could be performed.

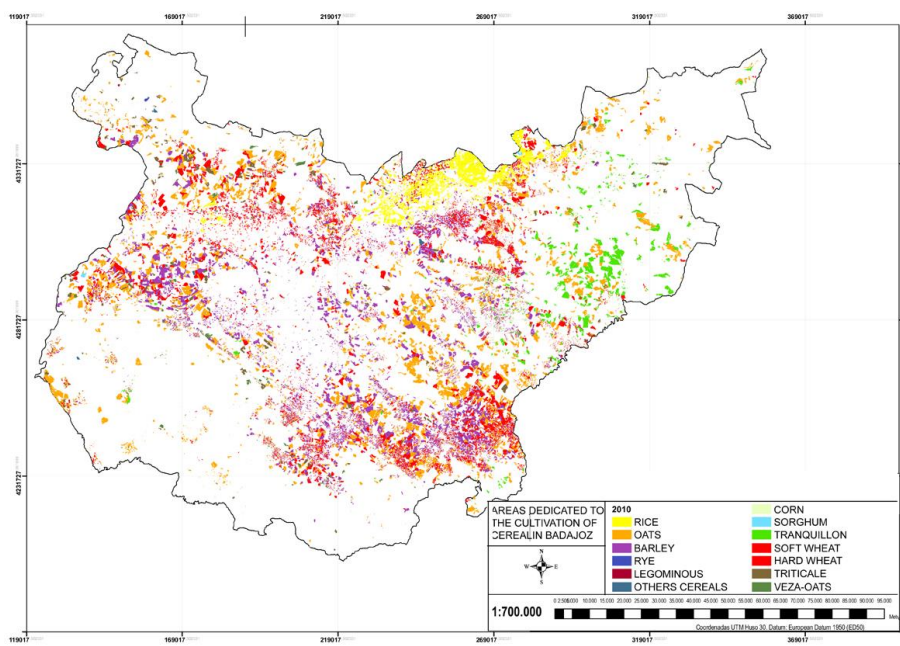


Fig. 1. Areas dedicated to the cultivation of cereal straw in Badajoz, Spain

¹ In this study, free GIS software gvSIG (www.gvsig.org) was used.

For the next step, digital mapping was done of the areas dedicated to the cultivation of cereal straw. This information was acquired from the Ministry of Agriculture and Rural Development in Extremadura database (Fig. 1). The process data, provided by the Ministry of Agriculture and Rural Development of Extremadura to the GIS, allowed the mapping of 78,250 agricultural areas. The elaborate cartographical digital layer, updated in 2010, included the following information: identification code of the area, municipality, grain grown on the area, and surface of the area. Then the areas where wheat grows were selected, which enabled calculations and related statistics at provincial, district, and municipal levels.

To reflect quantified areas of Badajoz focusing on the supply of straw, the ratio of straw production per unit of cultivated area (tons of wheat straw per hectare) was calculated. The study titled, “Assessment of biomass production in Extremadura,” published by the Energy Extremadura Agency in 2007, was taken as a reference for the proposed methodology. It calculates the amount of free annual wheat straw (C_{pt}) according to the wheat production through the following formula,

$$C_{pt} = P_{trigo} \times 0.8 \times 0.52 \quad (1)$$

where C_{pt} is the annual quantity of free wheat straw (t) and P_{trigo} is the annual wheat production (t).

As shown, the amount of generated straw was determined based on the straw/product relationship, which was 0.8 for wheat, according to a previous study. Additionally, it is very important to note that the above formula calculates the amount of straw left in the field that is potentially exploitable for sustainable construction purposes, energy, *etc.* After this calculation, the percentage of straw that is consumed as feedstock has to be subtracted, leaving 52% of the total available straw (coefficient 0.52) in the field.

After calculating the amount of free available straw in Badajoz, the coefficient of straw production per unit of cultivated area (P) (tons of wheat straw per hectare) was calculated using the formula,

$$P = C_{pt} / S \text{ (t/ha)} \quad (2)$$

where C_{pt} is the annual quantity of free wheat straw (t) and S is the straw cultivated surface (ha).

To determine which area has the greatest supply of usable straw and continue with the analysis using GIS cartography, the information provided by the Ministry of Agriculture and Rural Development of Extremadura was consulted in cells of 1 hectare (raster format) (Fig. 2).

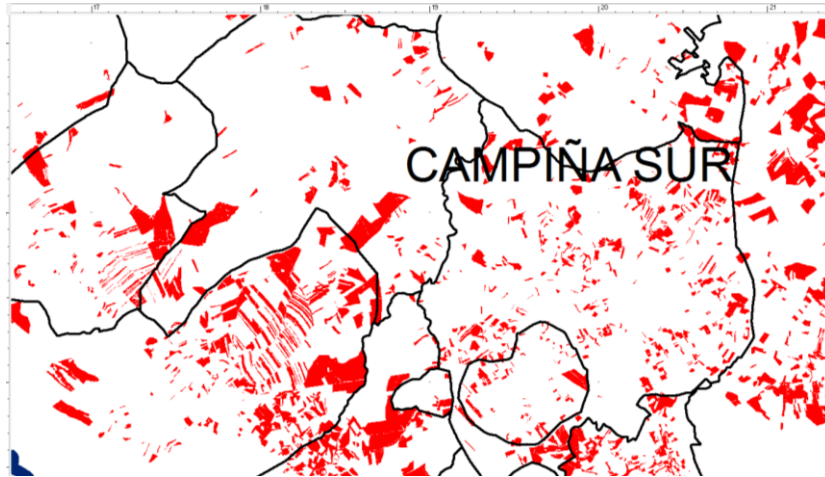


Fig. 2. Information in cells of 1 hectare (raster format)

This technique facilitates performing territorial calculations and statistics (district and municipal level), so that GIS can provide immediate results. Each obtained cell/pixel map (1 ha) represents an amount of annual free straw according to the expression:

$$C_{pt} = P \times S \quad (3)$$

With this equation, the amount of straw produced per area unit was calculated on the map, which allows the following quantities to be calculated through GIS:

- Amount of free straw produced by municipality and district
- Density of free straw production by municipality and district
- Tons of free available straw in a given radius of 30 km for each point in the province of Badajoz

Finally, using GIS, an analysis of other territorial factors can be performed, such as the density of the road network and the concentration of livestock farms by district.

RESULTS AND DISCUSSION

Determination of Usable Straw Supply in the Province of Badajoz

Following the methodology outlined in the previous paragraphs, once the agricultural enclosures dedicated to the cultivation of wheat in the province of Badajoz were located, approximate area of 77,152.54 hectares was calculated according to data (provided by the Ministry of Agriculture) analyzed by the GIS.

Prior data were compared with the data obtained from the 2009 Statistical Yearbook of the Ministry of Environment and Rural and Marine Affairs. According to it, in 2008, there was 101,598 ha of wheat grown in Badajoz and 102,425 tons of wheat straw was harvested (Table 1). It is important to note that the amount of straw counted (102,425 t) has commercial use, and it is marketed as food and for livestock.

Table 1. Production of Wheat Straw in the Province of Badajoz

Province	Surface (hectares)			Production (kg/ha)		Grain Production	Harvested Straw
	Unirrigated	irrigated	Total	Unirrigated	irrigated	(tons)	(tons)
Badajoz	100.181	1.417	101.598	3.345	3.845	340.554	102.425

Statistical Yearbook of the Ministry of Rural and Marine Environment of 2009 (Anuario de estadísticas del Ministerio del Medio Rural y el Medio Marino 2009)

Then, based on the production of grain in Badajoz, the amount of free annual wheat straw was calculated according to the equation:

$$C_{pt} = 340,554 \times 0.8 \times 0.52 = 141,670.464 \tag{4}$$

Comparing the amount of free straw (141,670 t) with the amount of harvested straw for commercial uses found in the Statistical Yearbook of 2009 (102,425 t), and assuming that the total amount of produced straw is the sum of both, it should be noted that the results are consistent with the proportions from the theoretical formula given by the Extremadura Energy Agency: 58% free straw and 42% harvested straw (livestock uses).

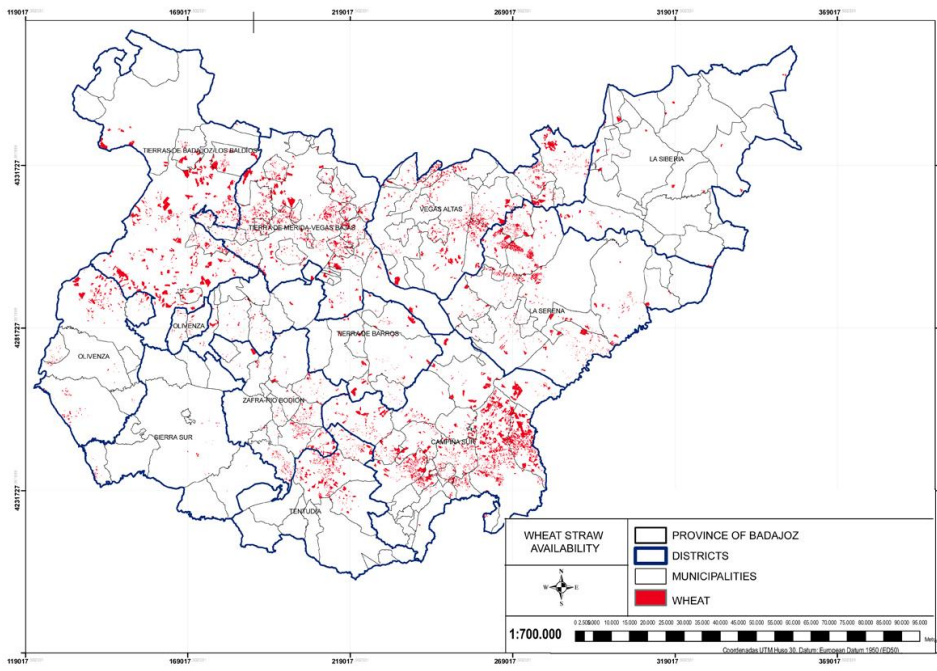


Fig. 3. Wheat straw availability

Considering the amount of free wheat straw produced in 101,598 ha of Badajoz, a coefficient of straw production per unit of cultivated area (*P*) was obtained:

$$P = 141,670.464 \text{ t} / 101.598 \text{ ha} = 1,394 \text{ t/year/ha} \tag{5}$$

Each cell/pixel in Fig. 3 has within it a net straw availability of 1,394 tons per year, as was discussed in the methodology section. Once the theoretical free straw in the digital mapping of the province of Badajoz was calculated, various calculations on a district/municipality level were performed using GIS.

Maps in Figures 4 and 5 show the availability of straw calculated for each of the municipalities and districts, respectively.

In Fig. 5 the results are organized by district. The amount of straw that exists in each district depends on the soil surface cultivation of wheat. To make a more accurate comparison between districts, the density of available vegetable fiber was calculated, *i.e.*, the amount of straw (tons) was divided by the surface area of each district.

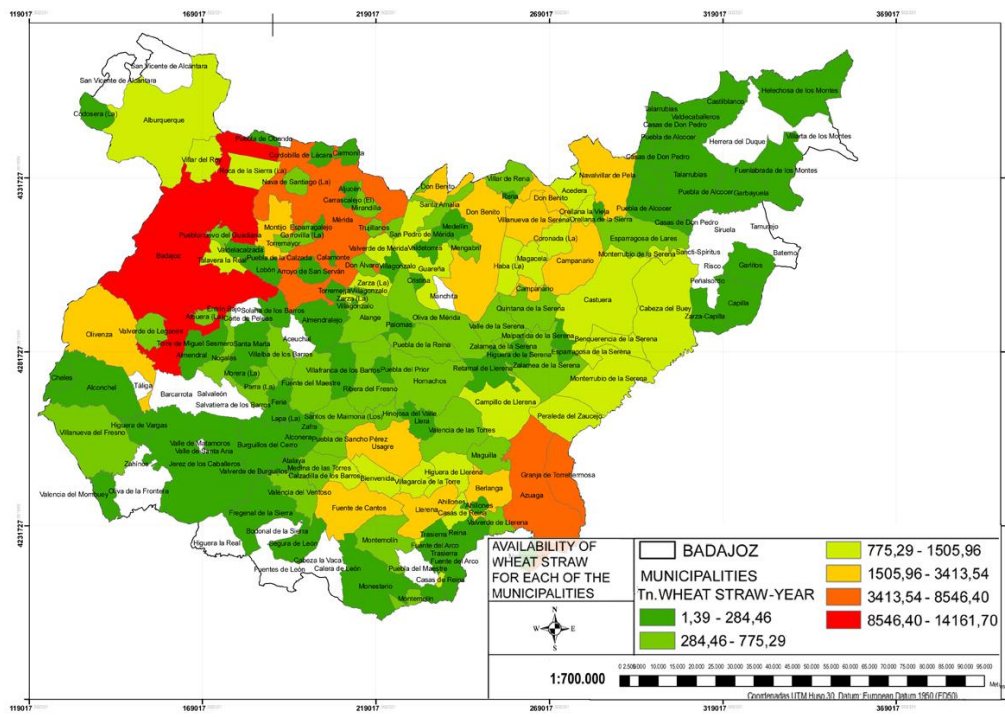


Fig. 4. Availability of wheat straw for each of the municipalities

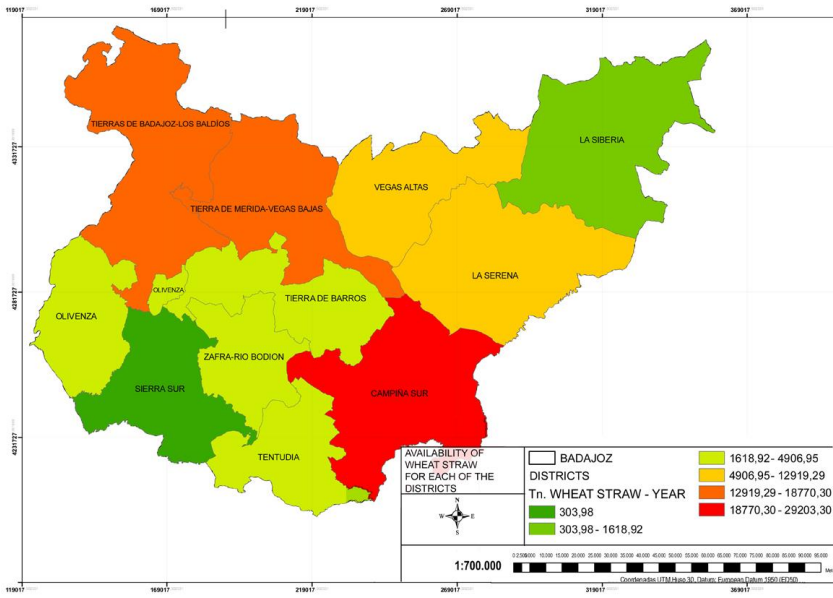


Fig. 5. Availability of wheat straw for each of the districts

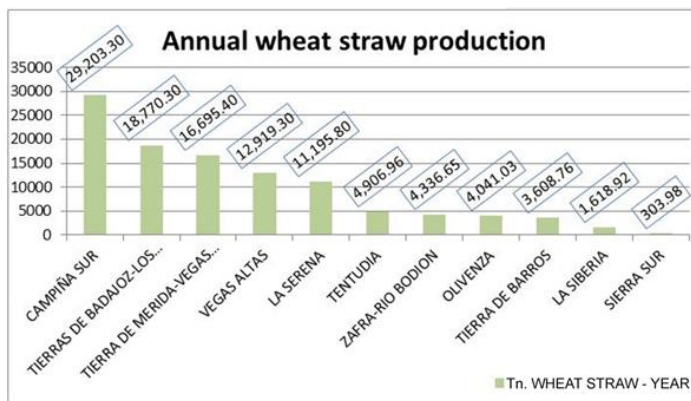


Fig. 6. Annual wheat straw production

Geographic information systems make it possible to calculate a raster output (map formed by cells or pixels), where the value for each output cell is a function of the values of all input cells around that location, at a specified neighborhood around it. To illustrate, consider a processing cell with a value of 5 (Fig. 7) in a neighborhood of 3 × 3 cells. The sum of the values of the neighboring cells (3 + 2 + 3 + 4 + 2 + 1 + 4 = 19) plus the value of the processing cell (5) is 24 (19 + 5 = 24). Therefore, the cell receives a value of 24 in the output raster in the same location as the processing cell in the input raster.



Fig. 7. Processing cell in a neighborhood of 3 x 3 cells

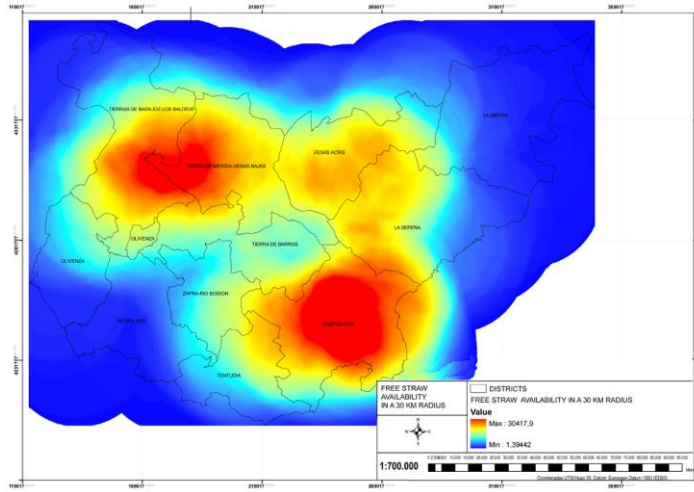


Fig. 8. Free straw availability in a 30 km radius

Applying the neighborhood analysis to this study, a map could be calculated in which each cell, one hectare in area, contained the value of the tons of available wheat straw for a given radius. To do this, the map in Figure 3 composed of cells of one hectare was considered. As calculated above, each cell has an availability of 1,394 tons of wheat straw per year.

The municipality analysis conducted by GIS calculated the sum of the free straw (1,394 t per cell), taking into account all of the cells in a 30 km radius, which is the distance considered profitable, as most conservative hypothesis, according to the report of FIVECO (Proyecto FIVECO, 2011) (Fig. 8). After that, statistics is carried out by district. The average availability of straw is determined within 30 km for each of the districts.

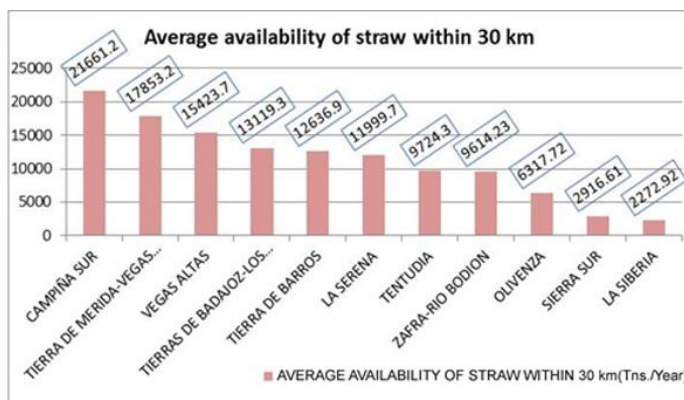


Fig. 9. Average availability of straw within 30 km

Analysis of Other Complementary Factors for the Location of the Straw Panel Manufacture Plant

To supplement the above analysis, additional factors for the location of the straw panel manufacturing plant were taken into account, such as the location of the main consumers of wheat straw (livestock) or the available road network.

Analysis of livestock consumer farms in the province of Badajoz

The analysis of the previous section took into account only free wheat straw, which is not used for food or livestock.

However, using the database provided by the Ministry of Agriculture and Rural Development of Extremadura, the farms that use wheat straw as food for livestock were determined.

The cited database has UTM coordinates for approximately 70% of farms. It enables the introduction of the physical location of the farms into the geographic information system. These locations can be found in Fig. 10.

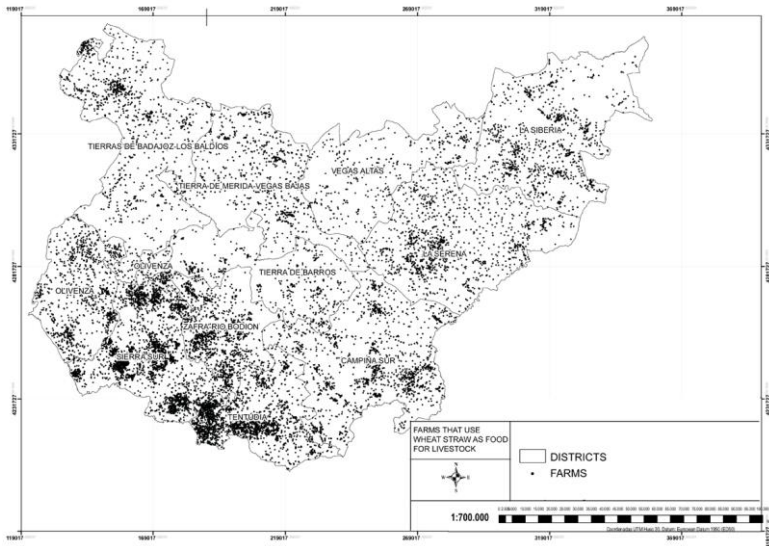


Fig. 10. Farms that use wheat straw as food for livestock

Through GIS, the density of farms per hectare was calculated, with a reference distance of a 30 km radius for each point on the map, as mentioned in the previous section. The results can be seen in Fig. 11.

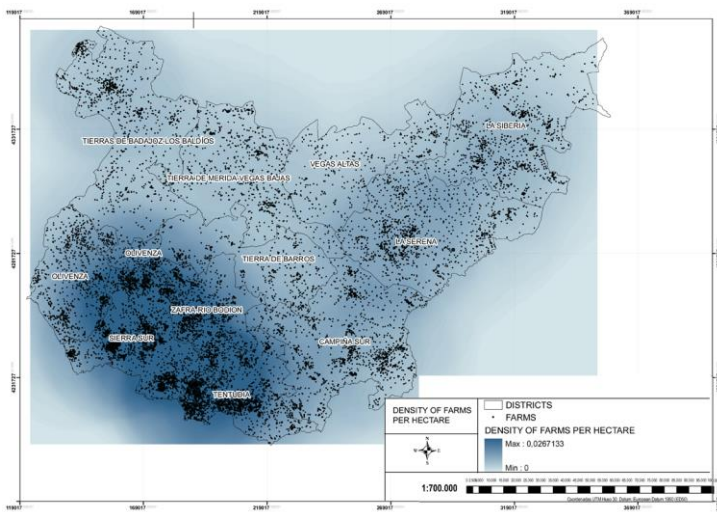


Fig. 11. Density of farms per hectare

Additionally, the road network in the province of Badajoz was entered into GIS digital mapping (Fig. 12). The road density was then calculated for each point on the surface of each district in meters of road per square meter in a 30 km radius from each point on the map (Fig. 13).

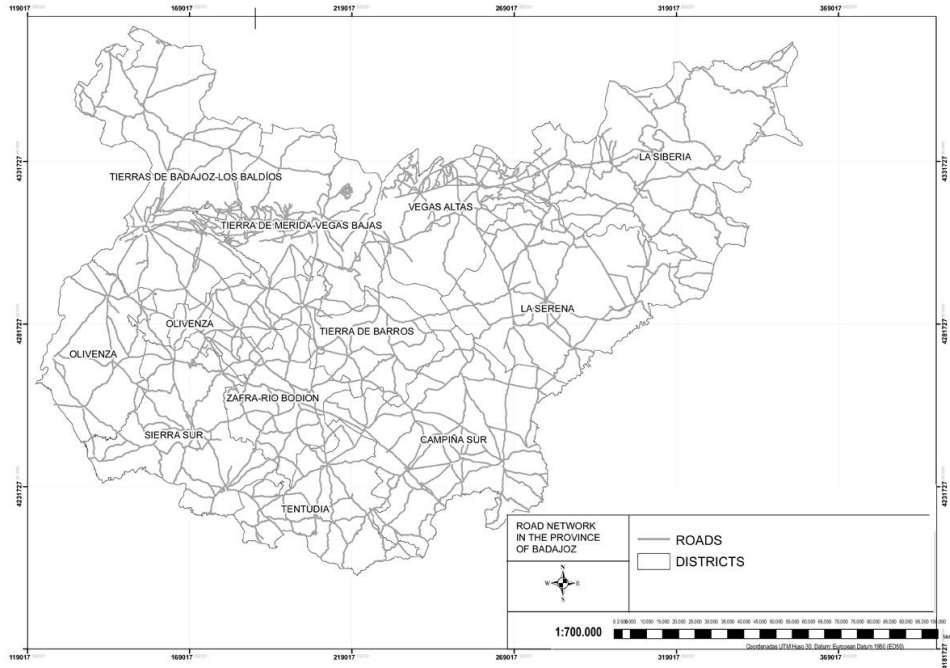


Fig. 12. Road network in the province of Badajoz

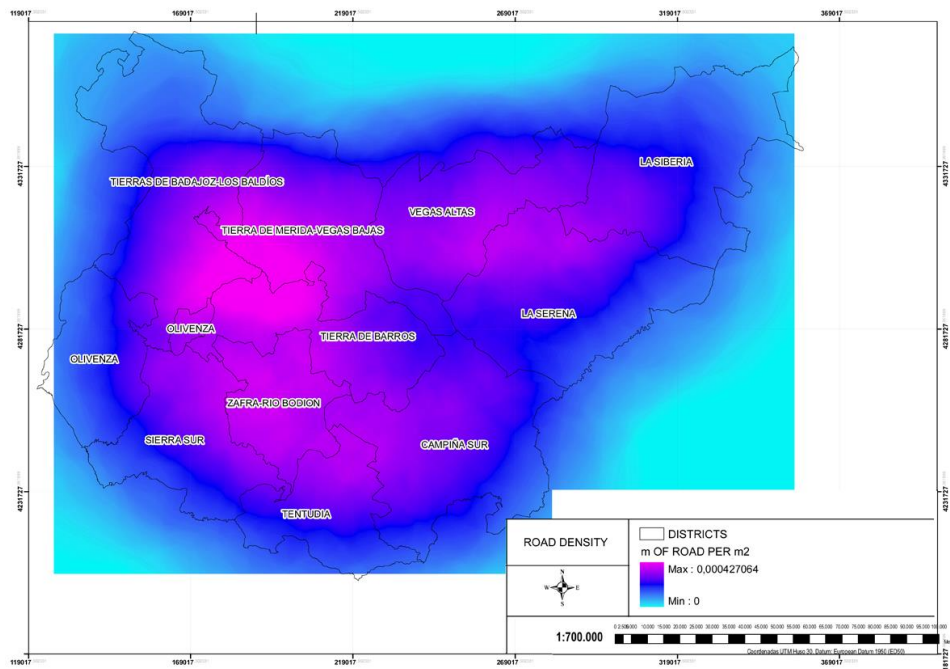


Fig. 13. Road density. Meters of road per square meter in a 30 km radius

Exploitation of Crop Residues for Energy Purposes

The analysis takes into account the potential use of plant residues as a raw material to obtain energy, having identified and analyzed this situation regarding ACCIONA Central, located in Miajadas (Cáceres). Technicians have suggested the use of corn stover as feedstock, for best energy performance. This situation does not represent a threat. Table 2 provides a summary of the most significant parameters related to the availability of free straw in each of the districts. In this table, the ranking of each of the regions in regard to the calculated parameters is detailed. The amount of straw in t/year by district is an absolute value that depends largely on the surface area of the region, and is not the optimal parameter for comparison between regions. This is why the data were divided by the area of each region, so that a relative value that allows a more direct comparison could be obtained (straw density in t/ha/year).

Table 2. Summary of the Most Significant Parameters Related to the Availability of Free Straw in Each of the Districts in Badajoz

District	Avg. availability R = 30 km (t/year)		Density straw: t/ha/year		Quantity straw: t/year	
Campaña Sur	1	21,661.2	1	0.1111	1	29,203.3
Tierra de Merida-Vegas Bajas	2	17,853.2	2	0.0799	3	16,695.4
Vegas Altas	3	15,423.7	3	0.0719	4	12,919.3
T. de Badajoz-Los Baldios	4	13,119.3	4	0.0655	2	18,770.3
Tierra de Barros	5	12,636.9	9	0.0229	9	3,608.76
La Serena	6	11,999.7	5	0.0423	5	11,195.8
Tentudia	7	9,724.3	7	0.0382	6	4,906.96
Zafra-Rio Bodion	8	9,614.2	6	0.0389	7	4,336.65
Olivenza	9	6,317.7	8	0.0282	8	4,041.03
Sierra Sur	10	2,916.6	11	0.0018	11	303.98
La Siberia	11	2,272.9	10	0.006	10	1,618.92

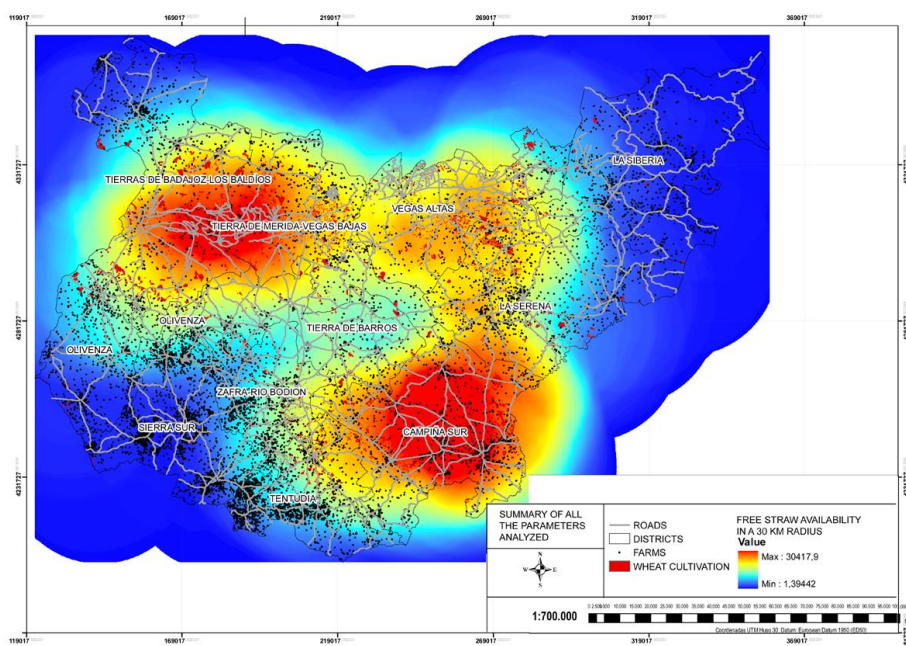


Fig. 14. Summary of all the parameters analyzed

A summary of all the parameters analyzed can be seen in Fig. 14. The statistical value with greatest impact was the mean free straw availability calculated for all the points in each region, with reference to a radius of 30 km. Since this is an average, it allowed objective comparisons between each of the regions. It is important to note that these values only take into account data from crops produced in the province of Badajoz to calculate the wheat straw available within a 30 km radius.

CONCLUSIONS

1. Given the data for available free straw, the Campiña Sur district showed the best features for the location of a straw panel manufacturing plant. Furthermore, the districts of Tierra de Mérida-Vegas Bajas, Vegas Altas, and Tierra de Badajoz-Los Baldíos were three other options, in order of feasibility. Available free straw was the most important parameter to be considered for an optimal zone.
2. From the standpoint of the concentration of livestock, preferred districts have a lower density. The results show that the Campiña Sur district had an average density of 0.0071 farms/ha, while Tierra de Mérida-Vegas Bajas, Tierra de Badajoz-Los baldíos and Vegas Altas had a lower density (less than 0.0048 operations/ha). From the point of view of the availability of straw, the results showed a trend in which greater supply areas, have a lower stocking density.
3. The data analysis of road density showed more uniform results across districts, which indicated that this parameter is the least important.
4. To determine the supply of cereal straw in the province of Badajoz, was taken into account the data for the single year 2008, as a representative year. Future studies about how might vary the supply of cereal year to year, and how might it deal with a drought that could potentially wipe out a year's supply, are required.

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