Environmental impacts of natural and conventional building materials: a case study on earth plasters

Paco Melià [a,*], Gianluca Ruggieri [b], Sergio Sabbadini [c], Giovanni Dotelli [d]

[a] *Dipartimento di Elettronica, Informazione e Bioingegneria, Politecnico di Milano, via Ponzio 34/5, 20133 Milano, Italy*
[b] *Università degli Studi dell'Insubria, Dipartimento di Scienze Teoriche e Applicate, via Dunant 3, 21100 Varese, Italy*
[c] *Disstudio, via Piolti de' Bianchi 48, 20129 Milano, Italy*
[d] *Dipartimento di Chimica, Materiali e Ingegneria Chimica "G.Natta", Politecnico di Milano, piazza Leonardo da Vinci 32, 20133 Milano, Italy*

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1. Introduction

The constant increase of the global human population, which may attain 9.6 billion by 2050 according to UN reports (UN, 2013), poses serious problems of primary resources exploitation, among other equally dramatic environmental pressures. The global materials use is particularly severe in the building sector, due to the massive use of minerals as raw materials (Krausmann et al., 2009). While, up to a decade ago, people were mainly concerned with pollution caused by industrial activities, nowadays the built environment is more and more perceived as responsible for a sensible portion of anthropogenic impacts (EPA, 2013). Thanks to an increased awareness of global environmental problems, policies aimed at reducing energy consumption in the building sector have been vigorously taken up (e.g., the Directive 2010/31/EU) and related research has been fostered (Pacheco-Torgal, 2014).

While environmental impacts of energy use have been drastically tackled, much less attention has been devoted to regulate the exploitation of non-renewable resources needed to produce building materials. Despite this, the awareness that synthetic construction materials have a substantial role in the environmental sustainability of buildings (Nansai et al., 2012; Van den Heede and De Belie, 2012) is rapidly increasing, especially when considering zero-energy buildings (Thiel et al., 2013) or passive houses (Dahlstrøm et al., 2012) where energy consumption during the operational phase is reduced to negligible amounts (Himpe et al., 2013). This is not surprising, because most conventional building materials, such as concrete, steel, and masonry, all need a fairly large number of technological operations to be produced on an industrial scale in a relatively cheap and affordable way. This entails large amounts of embodied energy (Wang and Shen, 2013) and a non-negligible consumption of fossil and mineral non-renewable resources (Cabeza et al., 2013). This is less true for wooden products (Salazar and Meil, 2009), although massive forest exploitation poses problems as well if not properly governed and planned (Espinoza et al., 2012); for many reasons, however, wood-based architecture is not so widespread in the majority of European countries.

In the last fifteen years, especially in Europe and USA, there has been an upsurge of interest in natural (Wang et al., 2014) and unconventional construction materials (Ashour et al., 2011) which have lower embodied energy than conventional ones (Pacheco-

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* Corresponding author. Tel.: +39 02 23993680.
E-mail address: paco.melia@polimi.it (P. Melià).

Torgal, 2014) and help reducing the exploitation rate of non-renewable resources (Milutienė et al., 2012). Indeed, many recent Life Cycle Assessment (LCA) studies have unequivocally confirmed that the most relevant phases in building life (Fig. 1) are the operational phase and the manufacturing of building materials, while construction, maintenance, renovation and end-of-life phases are much less impacting (Silvestre et al., 2013). While energy consumption is the dominant factor of environmental impact in the operational phase, the most relevant impact factor of building materials is the industrial process. For this reason, sustainable architecture should look for construction materials subject to the least possible number of technological manipulations, possibly of renewable origin or completely recyclable or reusable at the building end-of-life, and produced on-site or nearby to avoid long-distance transportation. These fulfillments are no longer perceived as unattainable, as testified by an increasing market of renewable, natural, recycled building products (Zuo and Zhao, 2014). Natural building materials have the additional advantage to reduce the risk of exposure to chemical hazards, another issue on which the attention of the green building community is increasingly focusing (Atlee, 2011).

The use of earth as a building material dates back to the Neolithic era, since it was readily available and easy to work, and still nowadays more than one third of the total human population lives in a building made of earth (CRATerre, 2013; Minke, 2012; Pacheco-Torgal and Jalali, 2012). Earth can be used as a raw material (e.g. pisé, adobe, cob) or fired to produce ceramic bricks. However, the construction of earthen buildings is most often confined to rural areas of developing countries (Ciancio et al., 2013; Pacheco-Torgal and Jalali, 2012). Furthermore, most building techniques based on raw earth are more labor intensive and need periodical maintenance; for this reason, during the 20th century, they were largely substituted by cement-based techniques. In more recent years, sustainable building design has in some cases recovered traditional techniques. Consequently, there has been an upsurge of interest in rammed earth walls (Bui et al., 2011; Taylor and Luther, 2004), adobe and unfired clay products (Binici et al., 2005; Bollini, 2012) and earth plasters as possible substitutes for cement and cement-lime mortars; for instance, earth plasters are meeting a renewed interest for their possible use in straw bale buildings (Ashour et al., 2011, 2010) and historic buildings (Hamard et al., 2013; Ruggieri et al., 2013).

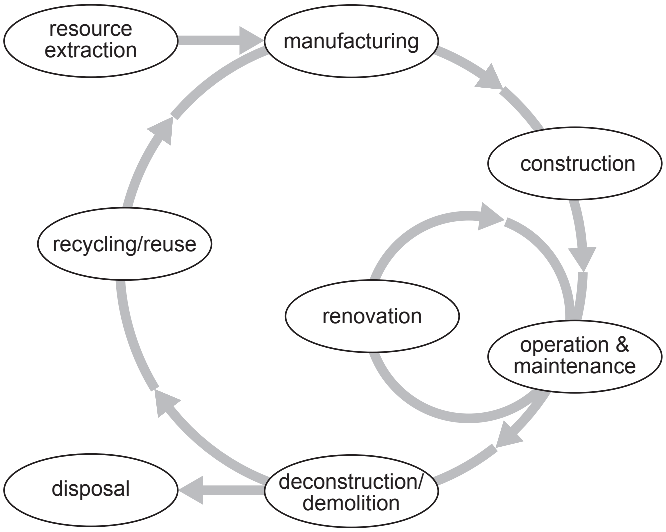

Fig. 1. Schematic life cycle of a building.

Scientific debate has recently emerged on earth materials, regarding which lessons from the past can be helpful for contemporary architecture (Morel et al., 2013). When used to coat indoor surfaces, earth plasters may show important advantages (Darling et al., 2012), in particular concerning the hygrothermal comfort (Akbari et al., 2012; Liuzzi et al., 2013; Minke, 2012): earth plasters can easily absorb water vapor in excess, or release it when it is scarce. Furthermore, they provide a peculiar tactile sensation, warmer than cement. Finally, since they may be easily prepared (sometimes directly with the earth excavated on site) the environmental impacts caused by their production can be expected to be lower than those of comparable conventional products.

Although in the recent literature some LCA studies on natural building materials have appeared (Ardente et al., 2008; Ip and Miller, 2012; Zampori et al., 2013), there is still a lack of extensive analyses such as those published on more conventional building materials (Chau et al., 2007; Zabalza Bribián et al., 2011). Moreover, to the best of our knowledge, there has been no environmental assessment of earthen materials, in particular of earth plasters. The aim of this study is to evaluate the environmental impacts caused by the production of earth plasters (based on clay) and to compare them with those caused by the production of conventional plasters based on cement or hydraulic lime by using the LCA methodology.

2. Materials and methods

2.1. Plasters

Plasters are usually applied in three layers: the first layer (scratch coat) is used to increase the homogeneity of the surfaces (e.g. bricks and mortar) and to provide a clutch for the second one; the second layer (leveling coat or brown coat), normally 15–20 mm thick, creates a plane surface on which the final layer (finishing coat) is applied. The last layer provides the desired look and color to the surface. Conventional plaster types include lime plaster (a mixture of calcium hydroxide and sand), hydraulic lime plaster (in which calcium hydroxide contains impurities, such as calcium silicates, enabling the lime to set also without exposure to air, e.g. under water) and cement plaster (a mixture of sand and Portland cement).

Earth plasters are composed of sand, clay and vegetal fibers. Sand provides the structure to the plaster and includes particles (most frequently of quartz) with diameter ranging from 0.0625 mm to 2 mm. Clay consists of particles <2 μm and is a very complex mix of natural elements, including hydrous aluminum silicates with traces of metal oxides and organic matter. It serves as the binding element of earth plasters. Clay and sand are mixed with natural fibers, which help to hold the plaster together and provide some flexibility to the plaster once dried. When indoor air humidity changes, the plaster changes its water content and the clay would tend to crack; the presence of fibers helps to reduce or avoid the formation of cracks. Natural or synthetic additives (cellulose, linseed oil, bitumen emulsion, lime, etc.) may be added for particular purposes (Minke, 2011), such as improving physical properties (shrinkage, absorption), increasing durability, preventing dusting (abrasion resistance), and changing the color.

The main concerns in the use of earth mortars as plasters regard shrinkage, abrasion, erosion (if applied on exterior walls) and absorption (Minke, 2011). Because in earth mortars the only binding agent is clay, the adhesion mechanism with the underlying wall is purely mechanical (Montana et al., 2014). The mechanical strength of an earth plaster is acceptable if after shrinkage there are no cracks through which water can penetrate into the underlying wall (Hamard et al., 2013). To reduce shrinkage, the amount of clay should be kept as low as possible, but this reduces also mechanical strength. The use of fibers improves the mechanical strength of earthen materials while minimizing shrinkage (Aymerich et al., 2012; Galán-Marín et al., 2010). Reinforcing fibers have also a positive effect on the hygrothermal behavior of earth plasters, increasing water absorption (Ashour et al., 2011; Maddison et al., 2009) and reducing thermal conductivity (Ashour et al., 2010). To improve the durability of earth plasters, binding agents other than clay can be added, such as mineral (lime, cement, bitumen) or organic additives (blood, casein, linseed oil), with good results in terms of resistance to erosion and abrasion (Minke, 2012).

We considered two different plaster types: a base (leveling) plaster, normally used for brown coating, and a finishing plaster. For each plaster type, we compared the environmental performances of conventional (hydraulic lime and cement) and earth plasters. Data for conventional plasters were derived from the Ecoinvent 2.0 database (Hischier, 2010) and are therefore to be considered as secondary data. On the contrary, for the production of earth plasters we used primary data provided by an Italian manufacturer producing artisan building materials. The earthen base plaster (see Fig. 2 for a scheme of the production process) is a premixed dry product that can be applied in a single layer. It is a mix of national (Italian) natural materials: clay, sand (silica and lime aggregates with diameter between 0.1 and 4 mm) and vegetal fibers (rice straw). The product is commercialized as a powder (ready to be mixed with water and applied) packed in 25-kg paper bags, and is available in two colors, ochre and sand. In this work, we analyzed only the ochre-colored version of the plaster. The finishing plaster (Fig. 3) is a product to be used for final coating of indoor vertical and horizontal surfaces. It is a mix of national and foreign natural materials: clay, sand (silicon and lime aggregates with diameter <0.3 mm) and a vegetal additive (<1% in weight). The vegetal additive is a food-grade, semi-synthetic compound used as a rheology modifier and water retention agent. The plaster is commercialized as a premixed dry product (ready to be mixed with water and applied), packed in 20-kg paper bags, and is produced in a variety of colors, depending on the particular clay used in the mix. We analyzed two different colors among those available: yellow and ochre. This allowed us to assess the influence of the transport on the environmental impact of the plaster: while the ochre clay is obtained by local providers (Piedmont region, northern Italy), the yellow clay is imported from Germany.

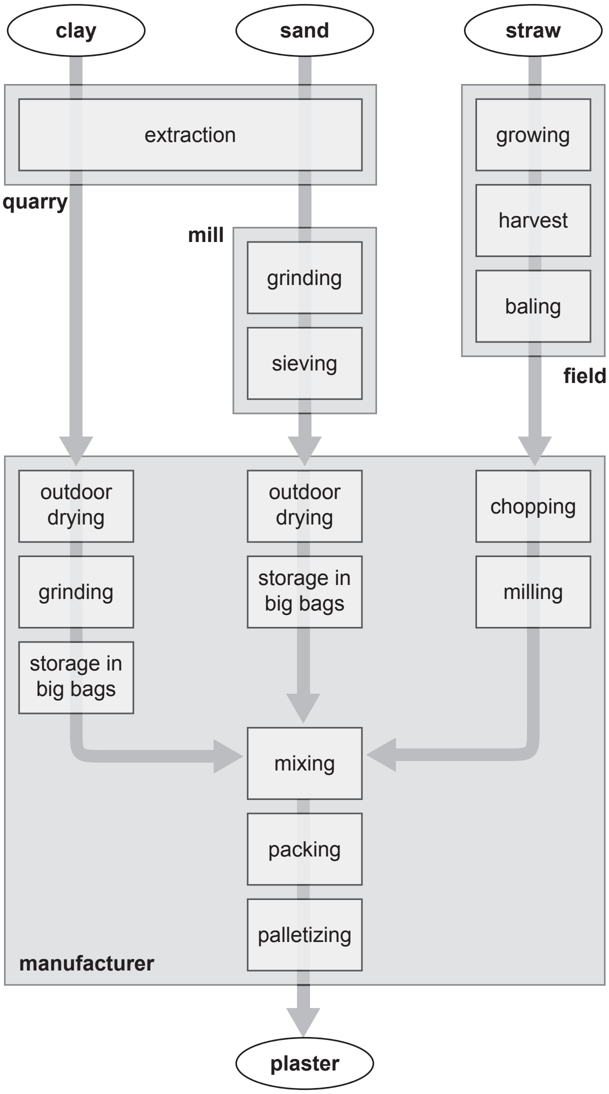

Fig. 2. Process scheme for earthen base plaster.

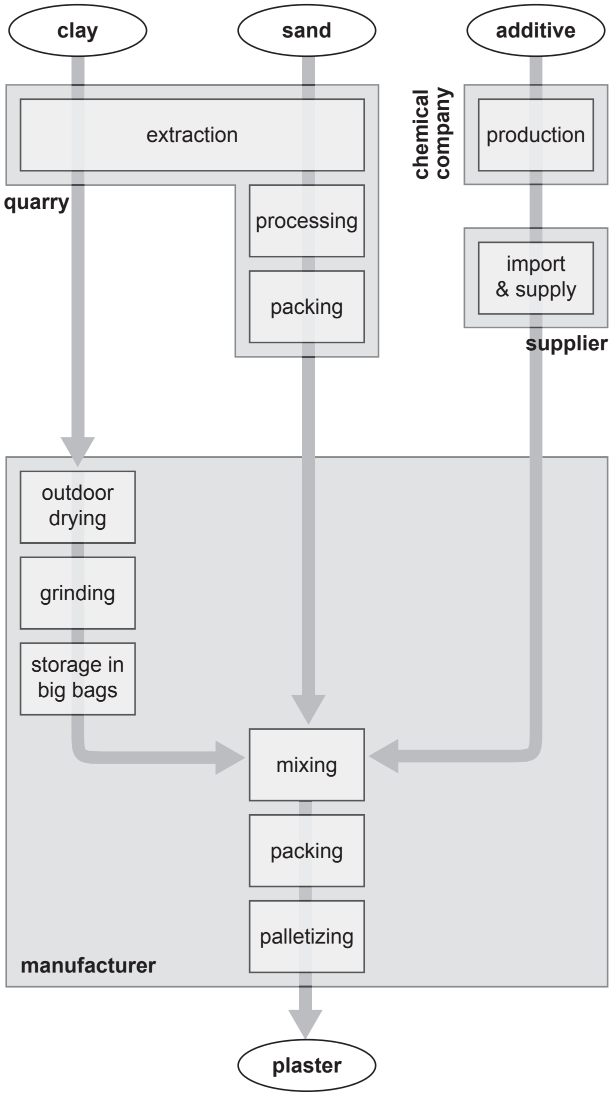

Fig. 3. Process scheme for earthen finishing plaster.

2.2. LCA methodology

The analysis presented in this paper follows the methodology defined by international norms (ISO 14040 and 14044). The assessment was performed utilizing SimaPro 7.3.3 software (Pré, 2013) adopting a cradle-to-gate perspective. LCA studies include four stages: goal and scope definition, inventory analysis, impact assessment and interpretation of results. A brief account of the most relevant details is given below.

In the first stage, the goal and the scope of the study must be unequivocally stated. The goal of this work is to assess quantitatively the environmental performances of different earth plasters and compare them with equivalent conventional (industrial) products. The study was motivated by a lack in the literature about the environmental pros and cons of earthen materials. In fact, the claim that these materials are environmentally friendly is more often based on qualitative judgments than on quantitative assessments. Clearly, the quality of the analysis is not perfectly equivalent for the different materials considered in this study, because the assessment of earth plasters is based on primary data, while results for cement and hydraulic lime plasters are taken from databases only.

2.3. Functional unit

The functional unit (FU) adopted in the analysis is the unit surface (1 m^2). Accordingly, the reference flux considered was the quantity of dry material applied on 1 m^2 of wall. We considered a standard thickness of 15 mm for the leveling plaster layer and of 3 mm for the finishing plaster layer. According to the cradle-to-gate approach, we did not account for the water used in the blend prepared for the application of the plaster. Reference fluxes for 1 FU of the different products are shown in Table 1, together with a summary of dry plaster composition.

2.4. Product system and system boundaries

For the earth plasters, the following process units were included in the system boundaries (Figs. 2 and 3):

1. fuel consumption in the extraction phase (excavation and handling)
2. packaging production
3. raw material and packaging transport to the manufactory
4. electricity and water requirements of the industrial process (including all machineries involved in the process).

Table 1
Reference fluxes and dry plaster composition for different products (the functional unit is 1 m^2 surface to be plastered).

Plaster type	Composition	Thickness (mm)	Reference flux (kg)	Product origin
Base plaster				
Cement	Cement/sand	15	30.00	– [a]
Hydraulic lime	Cement/hydraulic lime/sand	15	27.00	– [a]
Earth	Clay/sand/straw	15	21.75	Italy
Finishing plaster				
Cement	Cement/sand	3	6.00	– [a]
Hydraulic lime	Cement/hydraulic lime/sand	3	5.40	– [a]
Earth (ochre/ yellow)	Clay/sand/additive (from vegetable origin)	3	3.60	Ochre clay: Italy yellow clay: Germany sand: Italy additive: China

[a] Data for conventional plasters are taken from the Ecoinvent 2.0 database and are therefore to be considered as non-georeferenced average values.

2.5. Data requirements

The producer provided all data concerning distances, product composition, power and water consumption, work regime of the machineries, so these can be considered as good primary data and no allocation procedure was needed. Data regarding the composition of plasters were validated by one of the authors (S. Sabbadini), who is also a practitioner and helped develop the recipes. Data about power consumption and work regimes of the machineries was validated by direct inspection of the manufacturer site during production. The origin of raw materials was verified with the producer and distances calculated with the aid of proper software. Data regarding the impacts of the extraction of the raw materials, along with the relevant fuel consumption, were derived from the Ecoinvent 2.0 database and are therefore secondary data.

2.6. Impact assessment methodology

Environmental impacts were assessed using 3 midpoint indicators (Cumulative Energy Demand, Greenhouse Gas Protocol and Ecological Footprint) and one endpoint indicator (ReCiPe). The Cumulative Energy Demand (CED) is a measure (expressed in megajoules) of direct and indirect energy use over the entire life cycle of a product (Hirst, 1974; Huijbregts et al., 2010). It accounts for energy produced from non-renewable sources (fossil, nuclear, non-renewable biomass) and renewable sources (wind, solar, geothermic, hydro and renewable biomass). In our impact assessment, we used CED version 1.08 as implemented in Simapro 7.3.3. The Greenhouse Gas Protocol (GGP) measures the amount of greenhouse gases (in kg CO_{2eq}) emitted in the atmosphere and contributing to global climate change (Greenhouse Gas Protocol, 2011). In its version 1.01, it includes emissions from fossil and biogenic carbon sources, emissions caused by land use change and carbon uptake by plants over a 100-year time horizon. The Ecological Footprint (EF) measures environmental impacts in terms of land occupation (Wackernagel et al., 2002). In the context of LCA it is measured as the product of an area by a time (usually in hectares × years), resulting from summing up three major impact categories: direct land occupation for the production of natural resources, indirect land occupation related to nuclear energy use, and land occupation to absorb greenhouse gases emitted when burning fossil fuels and the limestone for cement production (Hischier, 2010; Huijbregts et al., 2008). We used EF version 1.01 in our assessment. Finally, ReCiPe (Goedkoop et al., 2009) is an impact assessment method allowing both midpoint (i.e. in terms of environmental pressures) and endpoint (i.e. in term of environmental impacts) assessments. Environmental effects are classified into three macro-categories (damages to human health, ecosystem diversity and resource availability). Impacts on those three macro-categories can be further aggregated into a single score after appropriate weighting. Three weighing sets can be used: 'hierarchist', 'egalitarian' and 'individualist', reflecting three different social perspectives based on the cultural theory of risk (Tansey and O'Riordan, 1999): the individualist perspective has a short-term horizon, focuses only on undisputed impact types and has scarce interest in impacts with low probability; the hierarchist one balances short and long-term horizons and is based on common policy principles; the egalitarian one is the most precautionary perspective, has a long-term horizon and considers also impact types that are not yet fully established (Goedkoop et al., 2009). In this work, we used ReCiPe endpoint version 1.08 with a hierarchic weighting set, which is considered the most balanced among the three. Aggregated environmental impacts are measured in 'points' (Pt), which are dimensionless figures. The scale of ReCiPe points is set in such a way that the value of 1 Pt is representative for 1/1000 of the yearly environmental load of an average world inhabitant (referred to the world population of 2000, i.e. 6.12 billion people). However, the absolute value of the points is not very relevant, as the main purpose of the method is to compare relative differences between products.

3. Results

The impacts of the different plasters in terms of CED are compared in Fig. 4 (see Table S1 in the Appendix A for detailed results). As for base plasters (Fig. 4a), the total energy embodied in 1 FU of earth plaster is equal to 22.7 MJ, less than half of those of hydraulic lime plaster (52.8 MJ) and cement plaster (45.5 MJ). The difference is less pronounced for finishing plasters (Fig. 4d), although the impact of earth plasters (8.2 and 6.4 MJ for the yellow and ochre version, respectively) is, again, lower than that of hydraulic lime (10.6 MJ) and cement (9.1 MJ) plasters. The largest impact component is, for all plasters, the energy produced from fossil sources, which accounts for 63–85% of the overall embodied energy. A remarkable difference between earthen and conventional plasters is in the content of energy from nuclear sources, which reflects a lower electric consumption in the productive process of natural plasters.

The different environmental performances of natural and synthetic plasters are even more striking in terms of Greenhouse Gas Protocol (GGP) (Fig. 4b,e). Greenhouse gas emissions for producing 1 FU of earthen base plaster (0.88 kg CO_{2eq}) are about one sixth of those associated to a FU of hydraulic lime plaster (6.37 kg CO_{2eq}) and cement plaster (5.86 kg CO_{2eq}). As for finishing plasters, carbon emissions of earth plasters are 0.45 kg CO_{2eq} for the yellow version and 0.34 kg CO_{2eq} for the ochre one, while those of hydraulic lime and cement plasters are 1.27 and 1.17 kg CO_{2eq}, respectively. Also this indicator shows that fossil fuels are the major impact source, accounting for 98–99% of the overall net carbon emissions. The large difference in environmental performances of synthetic and natural plasters stems mainly from direct CO_2 emissions during the calcination process in cement manufacturing (Van den Heede and De Belie, 2012).

The environmental performances of earth plasters outcompete those of cement and lime-based plasters also in terms of EF. The footprint of 1 FU of base earth plaster is equal to 4.2 m^2 yr, much less than that of hydraulic lime plaster (19.4 m^2 yr) and cement plaster (18.2 m^2 yr). The difference is remarkable also for finishing plasters, with the EF of earth plasters ranging between 1.1 (ochre) and 1.4 m^2 yr (yellow) and that of standard plasters ranging between 3.6 (cement plaster) and 3.9 m^2 yr (hydraulic lime plaster). Consistently with the results obtained with CED and GGP indicators, the largest footprint component is that related to the set-aside of land for sequestering carbon emissions, which accounts for 61–84% of the overall footprint.

The results of comparing the different plasters with the ReCiPe endpoint method (Fig. 4c,f) confirm the lower environmental impacts of natural plasters with respect to those of conventional ones. As for base plasters, the overall impact (aggregated under the hierarchist perspective) of earth plaster is equal to 142 mPt (millipoints), while those of hydraulic lime and cement plasters are 427 and 369 mPt, respectively. The difference is less remarkable for finishing plasters: the impact of earth plasters ranges between 42 (ochre) and 56 mPt (yellow), while that of conventional plasters ranges between 74 (cement plaster) and 85 mPt (hydraulic lime plaster). The largest impact components are the depletion of fossil fuels (35–57% of the overall impact) and damages to human health caused by climate change (22–48%).

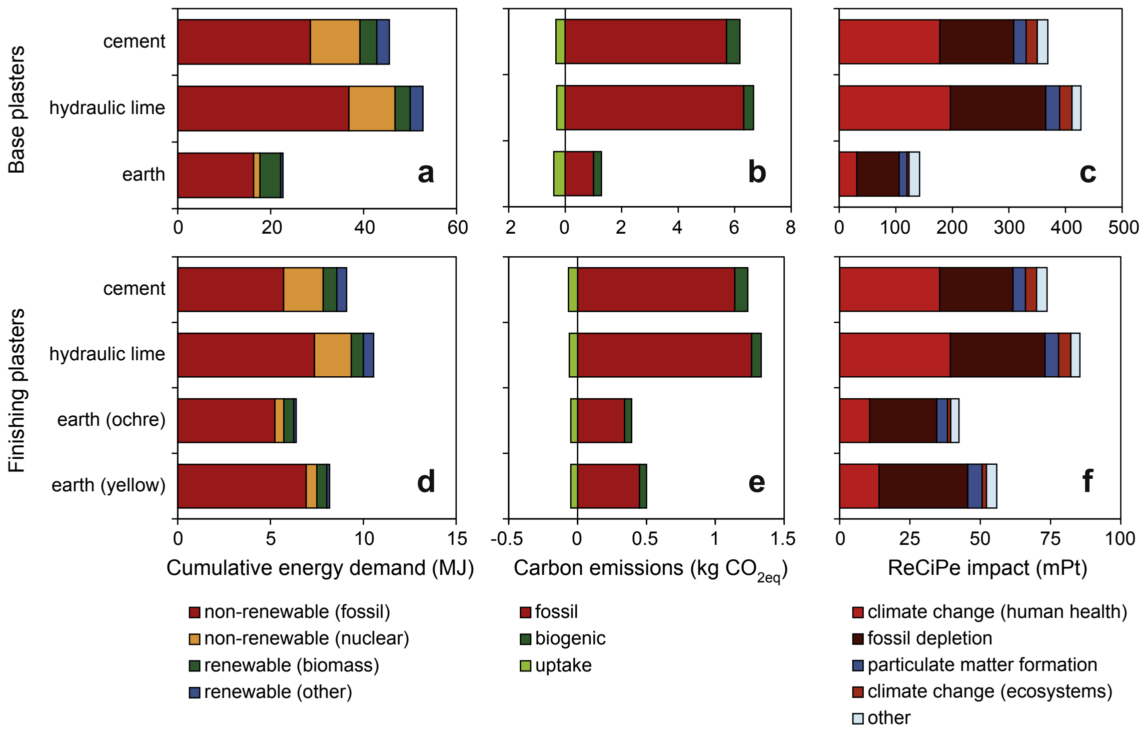

Fig. 4. Environmental impacts of different plasters (see Table 1 for reference fluxes) assessed in terms of cumulative energy demand (a,d), carbon emissions (b,e) and ReCiPe points (c,f). The category 'other' includes ReCiPe impact categories that are less relevant to the analyzed materials (see Table S1 for disaggregated results).

4. Discussion

The environmental performances of the different plasters, evaluated from a cradle-to-gate perspective via the four impact assessment methods, are summarized in Fig. 5. Overall, the life cycle impacts of the three earth plasters are substantially better than those of conventional industrial plasters, which are outperformed with respect to all indicators. This holds for both base and finishing plasters, but is particularly true for the earthen base plaster, which is characterized by very low energy intensity. In fact, the production of plasters from crude clay and sand is based on simple processes which require a relatively small amount of energy. In particular, the ingredients of earth plasters are raw materials which are simply excavated, sieved and mixed at room temperature, in contrast to cement and lime, whose production requires very high temperatures (up to 1450 °C for clinker production) and consequently high energy consumption.

As a consequence of the FU adopted for the analysis (1 m^2 of wall covering), the reference mass is markedly different for natural and conventional plasters (see Table 1). The main functions of indoor base and finishing plasters are surface leveling and smoothing, along with aesthetic rendering: accordingly, we considered that different materials are applied with the same thickness (15 mm for base plasters and 3 mm for finishing ones). As earth plasters have a lower density than conventional ones (also thanks to the presence of rice straw in the base plaster), the reference mass of the FU is much lower for earth plasters. Note that in the definition of the FU we did not take into account neither the hygrometric properties nor the effects on indoor air quality of the different materials, because it is difficult to link them to plaster thickness through a quantitative relationship. Thermal performances were also neglected in the FU definition, because a comprehensive energy budget cannot isolate plasters from the rest of the wall; furthermore, the role of plaster in thermal insulation is relatively negligible compared to that of the other layers forming the building envelope.

Our results are robust with respect to the choice of the specific indicator used for the impact assessment. The use of different impact assessment indicators provides different, and complementary, viewpoints to the assessment of the overall environmental impact of alternative design options. Fig. 5 clearly shows that, in this case, the ranking of the different materials in terms of environmental impact is the same (hydraulic lime plaster, cement plaster, earth plaster in decreasing order of environmental impact) independent of the indicator (CED, GGP or EF). The main reason is that, for relatively simple materials such as those analyzed in this work, the major impact sources are linked to energy use (fuel consumption and electric power) and, consequently, to CO_2 emissions into the atmosphere. The use of a multi-dimensional indicator, such as ReCiPe, in addition to the others which focus on a single impact dimension, corroborates this view. Multi-dimensional indicators can be useful for decision-making by revealing possible trade-offs between different impacts. In fact, the area needed to grow the vegetal component of earthen base plasters makes their impact on land occupation slightly higher than that of conventional ones (about 1.5 times larger: see results on agricultural land occupation in Table S1). However, the magnitude of these impacts at the endpoint level (i.e. in terms of final damage to human health and environment) is largely negligible both in absolute and in relative (compared to the other impacts) terms. At the endpoint level, only three impact categories are indeed relevant: climate change and particulate matter formation (damage to human health), climate change (damage to ecosystems) and fossil depletion (damage to natural resources).

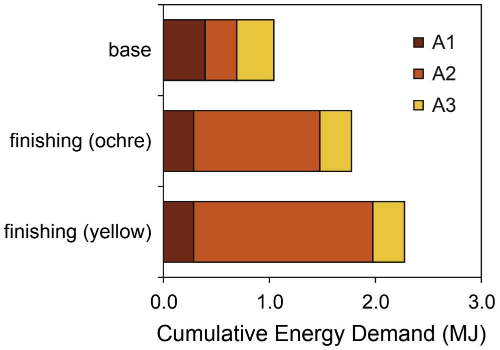

Fig. 6. Disaggregation of the cumulative energy demand of the three earth plasters into the three production phases identified by the EN 15804 standard (see text for details). Figures refer to a functional unit of 1 kg for all plasters.

As the analysis shows, transport is very important, at least in relative terms, in determining the overall impact of earth plasters. This is particularly evident if one compares the environmental impacts of the three earth plasters (which are comparable with respect to both material composition and productive process) by disaggregating them into the major phases identified by the recent European standard EN 15804 for environmental product declaration of construction products: A1 (supply of raw materials), A2 (transport, from the production sites to the manufacturer) and A3 (manufacturing, i.e. mixing of the ingredients and packing of the

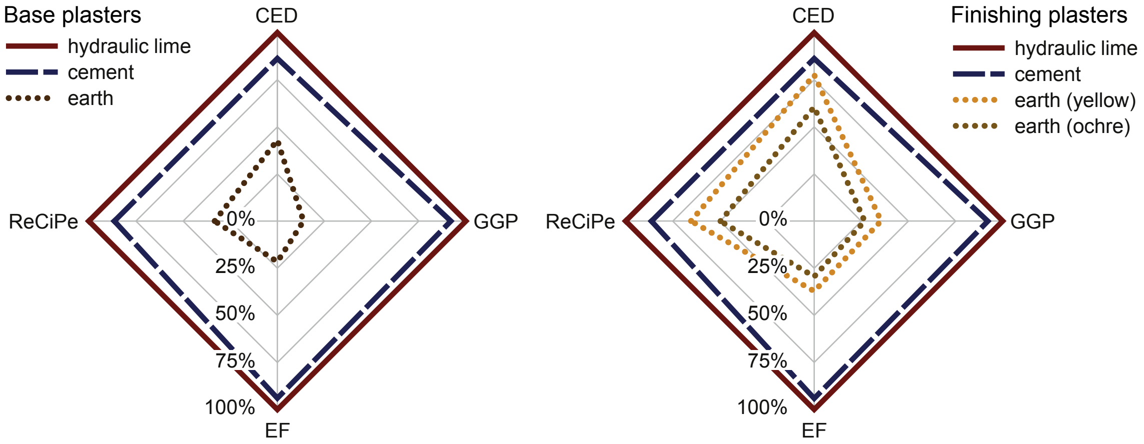

Fig. 5. Overall environmental impact of different plasters in terms of cumulative energy demand (CED), greenhouse gas protocol (GGP), ecological footprint (EF) and ReCiPe indicator.

final product). Fig. 6 shows the CED of 1 kg of each plaster. In the production of base plaster, energy consumed for transporting raw materials from the extraction sites and the field to the manufacturing site accounts for about one third (29%) of the total energy demand. On the other hand, transport accounts for 67% of the energy necessary to produce the ochre finishing plaster, and even for 74% of that required to produce the yellow one. The relative impact of transport does not change significantly if impacts are measured with other indicators (GGP, EF and ReCiPe; results not shown), ranging between 24 and 41% for the base plaster, 62–73% for the ochre finishing plaster and 70–80% for the yellow one. The large difference stems from the different distances traveled by the raw materials: gravel, clay and straw used to produce the base plaster come from the same province where the manufacturer is located (about 60, 14, and 24 km for the three components, respectively); the sand used for the finishing plasters comes from central Italy (ca. 500 km away), while the clay comes from northern Italy (ca. 250 km) for the ochre plaster and from Germany (about 530 km) for the yellow one. These results highlight that the use of raw materials of local origin is of paramount importance for natural building products such as earth plasters, otherwise there is the risk of nullifying their environmental benefits. Of course, the architectural relevance of specific aesthetic choices, like the color of the finishing plaster in the present case, cannot be completely neglected; therefore, a fine balancing is required between different, and sometimes contrasting, goals.

With respect to data quality, it should be noted that, while the life cycle inventory of earth plasters is based on primary data provided directly by the producer, the inventory of conventional plasters is based on database entries (Ecoinvent v. 2.0). For this reason, figures for conventional plasters should be considered only as average reference values. On the other hand, figures for earth plasters are specific to the products considered in our study and actual impacts might vary depending on the specific manufacturing site and the origin of the materials. Nonetheless, because the productive process is relatively easy from a technological point of view, the only data which are strongly site-specific are those relative to transports, while the other inputs should be considered as generally valid, at least for most developed countries.

The LCA methodology provides a valuable tool to compare the environmental performances of conventional and natural building materials. In our study, the superior environmental performance of earth plasters with respect to conventional cement and hydraulic lime plasters was supported by a broad range of environmental indicators. Although the amount of plaster used in a building is not dominant, especially compared to structural materials, the choice of a natural finishing material may contribute to increase the environmental sustainability (along with the interior comfort) of a building.

5. Conclusions

This study compared the environmental impacts of earthen plasters (based on clay) with those of conventional industrial plasters (based on cement or hydraulic lime) using the LCA methodology. Plasters were evaluated from a cradle-to-gate perspective via midpoint (Cumulative Energy Demand, Greenhouse Gas Protocol and Ecological Footprint) and endpoint (ReCiPe) indicators.

According to the results of the analysis, the considered earth plasters outperform conventional industrial plasters with respect to all indicators. In fact, the major impact driver of plaster production is energy consumption; producing plasters from crude clay and sand requires a relatively small amount of energy, while producing conventional plasters is more energy-intensive, as the production of cement and lime requires very high temperatures. The impacts of earth plasters are slightly higher than those of conventional ones in terms of agricultural land occupation (to grow the natural fibers necessary to improve mechanical strength and reduce shrinkage in earth plasters), but the magnitude of these impacts is largely negligible in terms of damage to human health and environment. On the other hand, transport represents an important proportion of the overall impact of earth plasters: finding local sources of raw materials is therefore crucial to maximize the environmental benefits of natural building products.

Acknowledgments

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Glossary

CED	Cumulative Energy Demand
EF	Ecological Footprint
FU	functional unit
GGP	Greenhouse Gas Protocol
LCA	Life Cycle Assessment.

Appendix A. Supplementary data

Supplementary data related to this article can be found on line.

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