Environmental, social and economic sustainability of bamboo and bamboo-based construction materials in buildings

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\textbf{ABSTRACT}

Bamboo is a natural building material that can be found in the tropical to mild temperate regions. It has been used from ancient times for its natural strength and flexibility. The renewed interest during the 1980s in bamboo as a construction material has revitalized bamboo not only as a cheap material but also as a durable material. Many bamboo-based building materials have also been developed which is more suitable for the modern construction needs. Bamboo has many environmental benefits which has made it a favorite green building material. This review critically studies not only the environmental aspects when bamboo is used as a building material but also its social and economic aspects, to understand its sustainability impact.

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\section{1. Introduction}

Bamboo is a giant grass. It is an important non-timber forest product which has multiple uses for people. One of the most prominent uses of bamboo is in construction. Bamboo has been used as a construction material from ancient times, especially by people who live in places where bamboo grew naturally and abundantly. In ancient times bamboo was used to build houses because of its natural strength and flexibility. In the modern context the aesthetics of bamboo also plays an important role. The interest in bamboo as a building material renewed during the global shortage of housing materials, especially the timber industry, in 1980s (Rao et al. 1995; Tadesse 2006\textsuperscript{a}; Basumatary et al. 2015; Nurdiah 2016).

Bamboo grows naturally in tropical, sub-tropical and mild temperate regions of Africa, Asia, America and Oceania as shown in Figure 1 (Clark 2006; Escamilla and Habert 2014; Shah 2014). There are a total of 1575 species of bamboo (Ohrnberger 1999; Suhaily et al. 2013) with 1200 species of woody bamboo (Bystriakova et al. 2003; Basumatary et al. 2015; Nurdiah 2016). Out of these, only 20–38 species are useful in construction, with Moso bamboo (\textit{Phyllostachys edulis}), Guadua (\textit{Guadua angustifolia} Kunth) and Giant bamboo (\textit{Dendrocalamus asper}) being the most important, being the strongest and largest of them all (Schröder 2012; Escamilla and Habert 2014; Benton 2015).

Bamboo could be used to make all parts of the house from structural walls and columns, to woven roofs to doors and windows (McClure 1981). In the olden times, bamboo was used in combination with other natural construction materials like wood, clay, lime and grass. Recently, it is used in combination...
Bamboo is strong and lightweight, and can often be used without processing or finishing (Gichohi 2014). Even though the natural round and hollow form of bamboo poses some problems during construction, especially for connections, its structural properties and environmental benefits make it a prime-building material candidate for sustainable construction. Many studies and tests have been carried out to overcome the issues in construction, which ranges from innovative connection details to composite materials. Decades of research by bamboo practitioners has validated that, when treated and used properly, bamboo is a sound structural and engineering material, which, due to its strength, flexibility and versatility, is a suitable material for use in housing (Kibwage, Frith, and Paudel 2011).

Nowadays bamboo is being addressed as a building material that can contribute to sustainable development. It is uniquely qualified because of its environmental, social and economic benefits. In this paper the environmental, social and economic aspects of bamboo construction material have been critically reviewed to understand its impact on sustainable construction. A comprehensive review of available published materials has been carried out. The review focused on the sustainability aspects of bamboo as building material only, and the findings were grouped under the environmental, social and economic aspects of sustainability. Studies which did not pertain directly to bamboo as a building material were not included in the study. The review includes journal papers, conference and workshop papers, review papers, theses, books, reports, informative flyers/booklets and information available on the internet.

### 2. Bamboo and bamboo-based construction materials

Bamboo has been used as a construction material due to its easy availability, ease of workability and its strength. Bamboo is stronger as a tensile member and it is recommended for use as horizontal members less than 3–3.6 m long without middle support (Nwoke and Ugwuishiwu 2011); potentially withstanding up to 3656 kg/cm2 of pressure (358.53 MPa) (Paudel 2008). A study showed that the tensile strength of bamboo is about 28,000 N/m2 (0.028 MPa), which is similar to steel (Nurdiah 2016). The strength of bamboo however depends on the species (Kyakula and Gombya 2008; Paudel 2008; Leake et al. 2010), as it depends on the age, diameter, wall thickness, position of load, radial position from outside to inside and levels of water (Asif 2009; Ibrahim 2010; Mahdavi, Clouston, and Anwade 2011). As shown in Table 1, different bamboo species have different mechanical properties.

The renewed interest in the past four-five decades has led to change in the forms in which bamboo is used and the final outlook of the house has changed a lot as well. Figure 2(a–c) show the progression of bamboo use from traditional to current style.

In traditional construction bamboo can be used as whole culms, split lengthwise, pressed flat or woven into mats (Bystriakova et al. 2003). The bamboo is usually joined by lashing with vines, split bamboo or rattan (Ham 1990; Larasati, Ihsan, and Mawardi 2013), this makes for a relative weak joint between bamboo poles. Often the joints are built, in vernacular contexts, throughout with tied ropes or by incisions of the bamboo, simple to realize but not suitable to transmit the entire bearing capacity of the bamboo elements (Sassu et al. 2016). In Indonesia, plastered bamboo houses were developed in early twentieth century which used wooden skeleton and bamboo woven mat on the outer skin. The woven mat was...
plastered so that, the wooden frame could be seen from the interior and the exterior side looked like a brick wall construction (Widyowijatnoko 2006).

This is very similar to the traditional construction system found in some South American countries. This traditional construction system in El Salvador and Colombia has lasted centuries without substantial changes (Prieto, Mogollón, and Farbiarz 2001; López, Bommer, and Méndez 2004). Bahareque consists of timber vertical elements and horizontal timber, cane or bamboo elements, with mud infill and finished with plaster. Though in some cases like in Ecuador, the warm tropical climate makes it unnecessary and bamboo houses need little more than the split bamboo walls for privacy and ventilation (DeBoer and Groth 2010; Sassu et al. 2016). Figure 3 shows the bahareque techniques of Indonesia and Colombia.

When interest in bamboo was renewed, it was used as cheaper substitutes for timber. They were used for constructing cheaper housing in developing countries. Due to the early interest and studies, various bamboo-based construction materials were developed like laminated bamboo, bamboo-reinforced concrete and others. These composites are very homogeneous in quality and can be tested and calculated in the manner of timber constructions (Krötsch 2013; Lobovikov et al. 2007) and they have better strength and termite-resistant quality than untreated bamboo (Deka, Das, and Saikai 2003). Nowadays, these materials are also called biocomposites, and can be divided into three categories (Suhaily et al. 2013):

1. Conventional Biocomposite: Chipboard and Flakeboard, Plywood and Laminated boards, Medium Density Fiberboard, Hybrid biocomposites;

Figure 2. (a) Archtype traditional bamboo construction in Philippines (Flander and Rovers 2009). (b) Modern plastered bamboo house in Colombia (Flander and Rovers 2009). (c) Modern bamboo house incorporating bamboo composite flooring in Indonesia (Green Village 2016).

Figure 3. Traditional Bahareque technique – Indonesia (left) (Widyowijatnoko 2006) and Santiago de Maria, Colombia (López, Bommer, and Méndez 2004).
Advanced Polymer Biocomposite: Thermoplastic-based bamboo composites, Thermoset-based bamboo biocomposites, Elastomer-based biocomposites;

Inorganic-based biocomposites: inorganic binders – gypsum, portland cement and magnesia cement.

Studies have shown that bamboo, either small diameter or splits, can be used as reinforcement in concrete (Hidalgo-López 2003; Asif 2009). A qualitative study showed that it is possible to use bamboo for modest housing by using split bamboo as reinforcement by following the design for steel reinforcement concrete (Sabnani, Latkar, and Sharma 2013). But the experimental structures built by Prof. H.E. Glenn in the 1950s using small diameter bamboo and bamboo splits, failed due to the de-bonding effects between bamboo and concrete mix (Hidalgo-López 2003; Hebel, Heisel, and Javadian 2013b, 2013a). However, an experimental study on manufacture of Oriented Strand Board (OSB) using Indonesian bamboo, Betung (Dendrocalamus asper Schult.) and Andong (Gigantochloa vermicillata Willd.), showed that OSB satisfying the physical and mechanical properties set by Indonesian code can be manufactured due to its good bonding property (Ibrahim 2010).

The use of these materials and the advancement in the preservation of bamboo from natural pests like rot and fungi has given to development of beautiful yet daring architectural marvels for which innovative joinery/connection have been developed. Many architects and engineers like Simon Velez, Marcelo Villegas, Jörg Stamm, Celina Llerena, Bobby Manosa and others use bamboo exclusively in their design (Garcia-Saenz 2012). Figure 4(a–c) show some examples of these designs.

It is interesting to see that more the bamboo is processed, with a value add-on, it becomes structurally stronger, aesthetically more pleasing, adds more social benefits and also becomes more costly. The following sections describe the environmental, social and economic aspects of bamboo-based construction materials in more detail.

3. Environmental aspect

Life Cycle Analysis (LCA) is the leading tool for assessment of impact that products and services have on the environment. Since there have been only eight LCA-based studies for bamboo construction materials (Escamilla and Habert 2014), including the reference article, instead of the LCA impact categories, this review looks at the following environmental aspects of bamboo-based construction material.

3.1. Renewability

Bamboo as a sustainable construction material arises from the fact that bamboo, when harvested in a sustainable manner, can have a more positive impact on the environment than other building materials. Sustainable harvesting can be achieved by maintaining a regular population of current live stems by

Figure 4. (a) Reinforced concrete joint developed by Simon Velez (Gatóo 2013). (b) Bamboo Pavilion by Celina Llerena (Bambubrasileiro 2003). (c) Resort made with Bamboo by Bobby Manosa (Manosa and Company 2016).
cutting selectively the 20% of mature stems since they will be replaced annually by an equivalent emergence of young shoots (Minae 1989). Different harvesting cycles can be recommended, depending on the anticipated logistical costs of transportation and harvesting, technical implications on potential harvestable bamboo, impact of bamboo harvesting on soil erosion and water conservation and the intended use of bamboo stems, like in India, where a four-year cutting cycle is recommended (ibid). Unlike other timber, bamboo can be harvested after 3–4 years after planting and yearly after that. In fact, harvesting of bamboo yearly keeps the clump or the bamboo forest healthy. When bamboo is harvested, the root system is unharmed and is ready to produce more shoots, which allows for a sustainable harvest of bamboo (Jianghua 2001; Asif 2009).

Bamboo has a very fast growth rate, so it has been regarded as suitable for afforestation (Mohamed 2003; Basumatary et al. 2015). But issue like loss of species variety has been noted (as undisturbed bamboo growth creates a thick canopy allowing little growth underneath (Minae 1989)) and low growth rates of bamboo have been noted in sites where there is lack of nutrient (Shibata et al. 2001). However, one study noted that, wherever bamboo is planted for reforestation and soil protection, it can be interplanted with other crops (Ministry of Forestry and Mines 2011) because a lot of leaves fall onto the surface providing fresh nutrients permanently for the whole vegetation system (Minae 1989; Acosta 2001; Arizaga 2001; Basumatary et al. 2015). Bamboo can be planted in areas that have been previously ravaged by deforestation or in flood plains (Basumatary et al. 2015). Although some bamboos can adapt to varying environments, most require relatively warm and humid conditions (mean annual temperatures of at least 15–20°C and annual precipitation of at least 1000–1500 mm) (Minae 1989; Scurlock, Dayton, and Hames 2000), there are still several species of bamboo that are drought-tolerant and grow in semi-arid regions (Ministry of Forestry and Mines 2011).

### 3.2. Carbon sequestration

By growing, bamboo takes in carbon dioxide and it in turn gets stored when used in the building. Although, bamboo lasts only 2–3 years in its natural form, chemical treatments to protect it from natural pests and the use of proper design elements to protect it from effects of climate can make bamboo last up to 30–40 years. Thus, when bamboo is used in a building, carbon is stored and not released into the atmosphere until the end of the life of the building. The carbon storage and sequestration rates for bamboo is 30–121 Mg per ha and 6–13 Mg per ha per year, respectively (Nath, Lal, and Das 2015). A study in China showed that bamboo (Phyllostachy pubescens) retains carbon longer than Chinese fir (Shaohui et al. 2006).

### 3.3. Embodied energy

Bamboo can be used as solid wood substitute materials, especially in manufacture, design and construction usage (Scurlock, Dayton, and Hames 2000; Bystrikaova et al. 2003), decreasing the pressure on forest resources. It can also reduce the current trend of construction industry’s use of high energy consuming building materials. Whereas the fabrication of bricks and cement consumes large quantities of energy and emits accordingly large amounts of carbon dioxide, the act of bamboo cultivation (which is sometimes called the act of growing architecture) is one of the best ways to reduce the green-house effect (Stamm 2001). Table 2 shows the energy requirement to produce various construction materials (Building Materials and Technology Promotion Council (BMTPC), n.d.; Laroque 2007). It can be seen that bamboo has the lowest energy requirement for production. The increased use of bamboo in construction can provide a 70% reduction of plantation timber used. A study in China expected that by 2015, bamboo will supplement the timber supply by 2 million m³ per annum (Chaomao et al. 2006). A study of a bamboo-structure residential building prototype showed that compared to typical brick-concrete building, the bamboo-structure building requires less energy and emits less carbon (Widyowijatnoko 2006).

### 3.4. Environmental pollution

Bamboo is considered to be environmentally friendly because it comes from a rapidly renewable resource (Gichohi 2014). The increase in bamboo use can help to reduce deforestation, encourage new and existing cultivators to grow more bamboo, utilize wasteland, unused land and river banks, which will result in better soil conservation and mitigation of flood disasters (Jianghua 2001; Nwoke and Ugwuishiwi 2011). This will not only improve the environment as bamboo has a negative impact on greenhouse effect, as it lowers the atmospheric and soil carbon content but this could also generate significant employment opportunities and thus promote the socio-economic status of the local people (Ham 1990; Ham and Shroyer 1993; Singh, Kumar, and Singh 2003).

The life expectancy of untreated bamboo has been found to be 2–3 years (Bystrikaova et al. 2003; Asif 2009; DeBoer and Groth 2010). This is because the

### Table 2. Energy requirement for production of construction materials.

| Building Materials | Density (kg/m³) | Energy for production (MJ/kg) |
|--------------------|----------------|-----------------------------|
| Concrete           | 2400           | 0.8                         |
| Steel              | 7800           | 30                          |
| Wood               | 600            | 1                           |
| Bamboo             | 600            | 0.5                         |
untreated bamboo is susceptible to rot fungi and invasion by wood-eating insects (Ham 1990; Bystriakova et al. 2003; Deka, Das, and Saikai 2003; Kyakula and Gombya 2008); it can also harbor disease-carrying insects (Ham 1990). Bamboo can be treated in two main ways: Non-chemical and chemical treatment (Liese 2002; Asif 2009; DeBoer and Groth 2010; Larasati, Ihsan, and Mawardi 2013). Traditionally, water immersion or smoking is used as non-chemical treatment methods. Other non-chemical treatment methods are painting with diesel, engine oil, Phenol Formaldehyde (PF) resin. In chemical treatment, treatment chemicals are penetrated into the bamboo either through injection or diffusion (immersion) methods. The treatment chemicals can be creosote oil, chromated copper arsenate (CCA), chromate-copper-boron (CCB), acid copper chromate (ACC), boron and boric acid mixture. The use of preservatives for bamboo and the handling of treated products pose potential risks to humans, animals and the environment (Liese 2002; Nurdiah 2016). Strict regulations on use of chemicals, dissemination of dangers about usage and disposal; and precaution during usage and disposal are needed to minimize this hazard.

4. Social aspect

Bamboo by being used as a construction material can have good impact on society. By developing a bamboo-based construction industry, it can not only preserve traditional skills but also create new income opportunity and ensure a much stronger social cohesion.

4.1. Traditional skills of construction and income generation opportunities

The socio-economic aspects of bamboo are significant because of the commodity’s role as a major non-wood forest product (Nasendi 1995): many people depend on this commodity as a source of income. The promotion of bamboo reduces deforestation, a key cause of poverty and urban migration (Ministry of Forestry and Mines 2011). By developing housing based on locally available building material, the skills of local people can be increased, which in turn will support them in income generation and prevent them migrating elsewhere, thus improving the social fabric (Ham 1990; Ham and Shroyer 1993). Since only basic carpentry, masonry tools and skills are necessary for the construction of bamboo houses (Kyakula and Gombya 2008; Nwoke and Ugwuishiulu 2011; Larasati, Ihsan, and Mawardi 2013), it can be easily taught to people with basic or no skill in the community. So, programs focused on promoting bamboo as a construction material combined with its plantation, harvesting and processing should be implemented, especially in places where bamboo has been naturally available. Although it is easier to calculate and pinpoint the environmental/ecological and economic aspects of sustainability of bamboo as a construction material, the social aspect is derived from these two, instead of being an entity in itself (Ham 1990; Hogarth and Belcher 2013; Effah et al. 2014).

4.2. Resilience to disaster

Bamboo as a building material has a positive social impact on the people affected by disasters as it can be used to speedily build houses that are disaster resistant and support livelihoods to recover from those disasters. Bamboo can help not only to reduce greenhouse effect by reducing carbon dioxide in the environment but it has roots that spread underground in all directions, turning land solid and preventing landslides that can be caused by heavy rain and earthquakes (Acosta 2001).

Bamboo has been regarded as a building material with which to construct earthquake-resistant buildings. An ideal structure for effective seismic resistance needs to be strong yet not very heavy, because the earthquake force imparted to a structure is a product of its mass and the imparted acceleration; therefore bamboo, which has a higher density but is lighter than timber because of its hollow nature is an ideal material as it will impart smaller earthquake force due to its smaller mass (Saleme and Navarro 2001; Kyakula and Gombya 2008). In El Salvador, the bahareque construction system (where bamboo is used as wall infill) has been identified as a building system which is seismically resistant to a remarkable degree as compared to adobe and the concrete block construction systems (López, Bommer, and Méndez 2004). An experimental study in Colombia, where two types of bahareque wall panels, one made of bamboo and one made of bamboo and wood, were tested for seismic performance, showed that panels with diagonal bracing showed better strength and stiffness, but in most cases the connections break before the walls fail (Farbíarz 2001). The study showed that there was no significant difference between the properties of all-bamboo panels and wood-bamboo composite panels. Another study done on the bahareque system of Colombia, showed that the popularity received by the construction system as an earthquake-resistant building was diminished due to the devastation caused by fire but by combining with materials like cement for plaster and improving the design, this system was added to the Colombian Code of Earthquake-Resistant Constructions (Sebá 2001). A study on building construction systems in four different countries of South America, namely, Peru, Ecuador, Colombia and Costa Rica, using bamboo as building material showed that its flexibility and lower weight combined to obtain a seismically resistant architecture (Saleme and Navarro 2001).
4.3. Social cohesion opportunities

Natural disasters affect people with low-economical resources bringing about a psychosocial depression that leads to abandoning of agricultural activities, which forces them to move to urban centers (Arizaga 2001). This is one of the biggest causes of increase of urban poor population. A study suggested planting of bamboo in the pluvials deposits caused by the sedimentation of flooding can be used to create income and thus rescue the dignity of people in areas devastated by El Niño (ibid). A study done in the mountainous area of Cuba showed that *Bambusa vulgaris* is very effective in control of soil erosion (Acosta 2001), which has the potential to prevent disasters from occurring in the first place. A study on housing implementation in India after a major flood showed that bamboo houses had a wider acceptance from local communities because bamboo houses allowed for better living conditions as they are better suited to the local climatic features of warm-humid areas (Lisa 2010). Thus bamboo can play a big role in bringing normality to life after disasters.

5. Economical aspects

The economical aspect of bamboo-based materials studied so far consist of the cost of the material and the income opportunities it creates. They are elaborated below.

5.1. Cost of material

Bamboo is often adopted as a cheaper construction material alternative. Although this might be true in cases where bamboo is available locally, the transportation costs could significantly increase construction cost and its sustainability in places where bamboo is not grown. This is true in the case of European markets. However, in China, the bamboo industry has become a backbone industry in economic development and poverty alleviation of rural areas, and a new growth point of economy in remote mountainous areas of southern China (Jianghua 2001). Also, due to bamboo’s new uses (bamboo flooring, bamboo bicycles, etc.) in industrialized countries in Europe and America, the cost of bamboo is increasing because the demand for bamboo is growing due to the increasing cost of other wood and actual tendency towards sustainability that bamboo can bring to the housing industry (Garcia-Saenz 2012; Larasati, Ihsan, and Mawardi 2013). Bamboo can be processed into modern products (engineered bamboo) that may successfully compete with wood products in price and performance (Lobovikov et al. 2007) but this will still be a niche market for the more affluent population.

An experimental study on using bamboo to create shelters with Tensegrity dome showed that bamboo can be used to create simple buildings, that are easy to assemble and lightweight which results in economy of material and labor cost (Ripper, Silva, and Moreira 2001). Similarly, a housing project in Nepal constructed prefabricated wood and bamboo houses that proved to be earthquake resistant, durable and more economical than other options like brick and concrete (Kesari 2006).

The concept of sustainable products and development of bamboo biocomposites can be considered a wise balance between the demands of society’s increasing demand for products, the preservation of forest health and diversity of material resources and benefits (Suhaily et al. 2013). The major issue is that the commercialization of most highly valued bamboo products has been identified to cause major impacts on sustainability of raw material production (Tadesse 2006b). When demand for bamboo increases, rapid and uncontrolled harvesting can lead to serious depletion of bamboo and deforestation. A study conducted in the northeastern Yunnan province of China showed that one of the major reasons for decline of bamboo forest (*Qiongzhuea tumidinoda*) was extensive logging of mature bamboo and ravaging of shoots (Wenyuan et al. 2006). Also, the addition of transportation from the country of manufacture to the country of use adds hugely to the embodied energy and cost, undermining the sustainable benefit of bamboo (Gichohi 2014).

5.2. Financial gain opportunities

The economic benefits of bamboo housing arises, not only from the low cost of bamboo as a material but also from the fact that it is a means of income for people who work in the bamboo industry, be it construction of houses or making engineered bamboo construction materials. These jobs include conventional agricultural jobs common in developing regions as well as higher-skilled jobs required to process the bamboo raw material into value-added products, such as furniture, housing, composites, etc. (Dagilis 1999). However, the benefits have not always reached the very poor; many researchers did not take into account that the users in their studies were poor people living in rural areas of tropical countries where bamboo grows, where steel bars for concrete are scarce or unavailable (Hidalgo-López 2003). In many places, like in Philippines where demand exceeds the supply, over-harvesting and premature harvesting are major problems (Ramirez 1995), and this will lead to degeneration of the bamboo forest.

6. Conclusion

For a long time bamboo has been “poor man’s timber”, so it became the choice of material for most low-cost or
cost effective housing. Using bamboo in construction or housing projects where bamboo is abundantly found has become a source of income for people who were already familiar with bamboo. By involving people in sustainable bamboo cultivation, it becomes another source of income for people who are still dependent on agriculture. The manufacturing of bamboo products for construction is another avenue for income. Bamboo can thus strengthen the self-reliance of local communities. Traditional construction technology was handed down from generation to generation, so it became a part of the socio-cultural structure of the people. Reviving such technology, further developing the technology and transferring it to the people who are already familiar with use of bamboo can strengthen the society. Bamboo can be used for speedy construction of houses, either permanent or temporary, in disaster stricken areas like post-earthquake area. It can also be used for prevention of soil erosion that will ultimately prevent disasters like landslides and flooding. By considering the beneficiaries of each step from planting and harvesting of bamboo, to its processing in industries and finally in construction, the income generation opportunities for each socio-economic strata of society can be included in any development project of bamboo.

For a sustainable economic and social development, ecological sustainability is a basic requirement. It is not the consumption of material resources per se, but much rather the resulting pollutant emissions that are currently regarded as an obstacle to sustainable development. The studies carried out so far have proven that the use of bamboo in construction indeed will promote sustainable construction because bamboo has many environmental benefits that can entice people to use it to improve their socio-economic standing. Although, ways to economically benefit the locals who are directly in contact with growing and harvesting of bamboo should be integrated into any construction business.

Overall, bamboo has the potential to be a sustainable building material but more studies are still required, especially dedicated to the social aspect of bamboo in the building context. During this study, it was observed that bamboo is generally considered to be synonymous with sustainability, but the explanation for such was not easily discernible. Additionally, the seismic property of bamboo housing has been well studied both theoretically and practically but studies regarding bamboo as a building skin are completely lacking. Additional studies are required to better understand the socio-economic aspects of bamboo-based construction materials. Another aspect of further study can focus on the built environment of bamboo buildings and the effect on living comfort of bamboo-based construction material.

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