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Bamboo composites: Material of the future

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Abstract—Bamboo is an important renewable resource on which around 2.5 billion people all over the world depend greatly for a wide range of products and livelihood. Bamboo has more than 1000 documented uses. About one billion people live in bamboo houses.

Bamboo, a tree-like grass, represented by about 1250 known species, is found in all regions of the world: tropical, sub-tropical and temperate except in Europe and West Africa. Bamboo accounts for approximately 25% and 20% of the total biomass respectively in the tropics and the sub-tropical areas. Bamboo has several unique advantages, namely: (i) ability to rejuvenate degraded areas; (ii) grows well in plantation models in harmony with other species, and hence there is no need for mono-culture; (iii) short rotation cycle of 2–5 years; and (iv) widely recognized traditional resource having quicker acceptability.

Panel composites made from bamboo have great potential due to their better strength, dimensional stability and other characteristics compared to panels made from several fast growing plantation timbers. IPIRTI is the premier Indian R&D institution working for development for bamboo composites. It has already developed technologies for several mat-based composites from bamboo including Bamboo Mat Board (BMB), Bamboo Mat Veneer Composite (BMVC), and Bamboo Mat Corrugated Sheets (BMCS). Whereas BMB and BMVC are being produced in some factories, technology for BMCS is being scaled-up for industrial production. Works relating to development of suitable application technologies and codes of practice are in also progress.

Additional positive aspects of bamboo-based panel materials are environmentally friendly reduction of pressure on forests through wood substitution; it is people friendly as it uses traditional resources; it enhances rural employment generation with participation of women and community development.

BMB technology developed at IPIRTI has been found to be an exemplary demonstration of implementation of Agenda 21 by the International Selection Commission of EXPO-2000 and was a registered Project around the World at the EXPO-2000 Hannover, Germany.

This paper discusses IPIRTI's R&D efforts related to development of bamboo composites and their relevance for people oriented development programs.

Key words: Bamboo composites; bamboo mat board; people and environmentally friendly technologies; wood substitution; employment generation; board properties.

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1. INTRODUCTION

India is the second most populated country in the world. With only about 1% of the world's forests, India supports 15% of world's human population and 16% of cattle population. The increasing needs of growing population and environmental awareness have put severe restrictions on management of forest resources. This has resulted in shortage of wood required in housing, transport and other sectors. Several non-wood alternatives like metal and plastics have serious limitations on account of high-energy requirements and non-bio-degradability. Moreover, long-term sustainable supplies of products can be met by use of bio-mass based materials alone [1]. To meet the increasing needs of the growing population a two-pronged approach is necessary. First, it is necessary to evolve a policy for production and efficient utilization of fast growing plantation woods [2]. Secondly, there is an urgent need for development of materials and products from non-wood renewable natural fibers as sustainable and environment friendly alternatives to natural wood.

Bamboo, a fast growing tree-like grass, found in abundance in several provinces of India is emerging as a material of high potential. Apart from being available in natural forests, bamboo is also raised as plantations, both pure and as under planting, and also in homesteads. Bamboo is also suitable for reforestation of degraded forest and other wastelands as well as abandoned shifting lands.

2. BAMBOO COMPOSITES

It has now been realized that bamboo produces biomass faster and has superior physical and mechanical properties compared to wood available from many fast growing wood species. Some earlier studies have revealed that bamboo in panel form is best suited to substitute wood in several applications. Development of effective technologies to produce bamboo-based panel material is now an important area of research not only in bamboo-growing countries but also in several other countries.

The first recorded production of panels from bamboo was during the Second World War to make ply-bamboo by hot pressing woven bamboo sheets coated with casein glues [3]. Almost at the same time research was initiated in India to develop synthetic resin bonded bamboo mat board [4]. More than 30 types of panel products, some of bamboo only and others of bamboo in combination with wood, other lingo-cellulosic materials and inorganic materials have been developed u[illegible] bamboo either as woven mats or slabs/strips.

3. DEVELOPMENT OF BAMBOO COMPOSITES IN INDIA

In India, research efforts to make building boards from bamboo were initiated i[illegible] mid-1950s at the Forest Research Institute, Dehra Dun, and several processes [illegible] evolved till early sixties [5] . However, industrial production of BMB in the country started in the mid-1980s following the development of technology for making BMB from the reed bamboos, *Ochlandra travancorica* and *Ochlandra rheedi*, by IPIRTI under a project sponsored by the All India Handicrafts Board [6]. To improve economic viability of the technology and enhance product acceptability, further research was conducted at IPIRTI under the project 'Bamboo Mat Board (India)' funded by the International Development Research Center (IDRC), Canada and a cost effective process was developed [7–10].

BMB technology has been further modified for manufacturing Bamboo Mat Veneer Composite (BMVC) made from bamboo mats in combination with veneers from fast-growing plantation species for panels thicker than 6 mm.

BMB are made from manually woven bamboo mats and hence production of BMB has immense employment generation potential particularly for rural and tribal women who can virtually 'weave money' at home. Thus, while BMB technology is environmentally sustainable it is also people friendly. The technology was assessed to be an exemplary demonstration of implementation of Agenda 21 by the International Selection Commission of EXPO-2000 and was registered as a Project around the World at EXPO-2000 Hannover, Germany [11].

Seeing the potential of the BMB technology, the Building Material and Technology Promotion Council (BMTPC) of India funded IPIRTI for a project for development of technology for manufacturing bamboo mats corrugated sheeting (BMCS) as an eco-friendly roofing material. Under this project, a pilot scale facility with a one-day light hydraulic hot press fitted with specially designed matching platens has been established at the Institute. Full size (0.9 m $\times$ 1.82 m) sheets manufactured at this pilot press have been used for roofing in several demonstration structures. Bonded with phenolic resin these sheets are very durable and possess decay, insect and fire resistant properties. BMCS has very high strength-to-weight ratio and has great potential to be used as roofing material in place of asbestos cement corrugated sheets which have already been banned in many countries on environmental and health considerations. Apart from roofing, BMCS has high use potential in wall panels, packaging, transportation, etc. The Institute is currently working in collaboration with BMTPC under a project funded by the Ministry of Environment and Forests, Government of India for up scaling the BMCS technology for commercialization. An Indian Patent has been applied for jointly by IPIRTI and BMTPC (Application no. 653/MAS/2001 dated 8th August 2001).

IPIRTI has collaborated with TRADA Technology of UK, under a project funded by DFID, in design development of low-cost bamboo shelter using split bamboo grid with cement plaster for walls, BMCS for roof with bamboo trusses, and BMB for panel door/window shutters. Under this project two demonstration structures have already been constructed at Bangalore [12, 13]. High shear modulus of BMB and BMVC can be advantageous in designing earthquake resistance houses [14].

3.1. Manufacturing process

The main raw material for making bamboo mat composites is the bamboo mat woven from thin strips, 0.6 to 1.0 mm, of bamboo called slivers. Mat weaving is done generally by women in rural/tribal areas as a part-time vocation to supplement family income. From bamboo splits, the epidermal layer is removed and slivers are made and air-dried. Slivers are manually woven into mats of different sizes and patterns. Herringbone is the most common weaving pattern in which slivers are at an angle of 45° with respect to the edges of the mat.

Bamboo mats are dipped in phenol formaldehyde resin having specific formulation incorporating preservative chemical to enhance termite and decay resistance. Resin coated mats are dried to a moisture content of around 10% either in drying chambers or industrial dryers. Dried resin coated mats are assembled in 2, 3 or 5 plies and hot pressed to produce bamboo mat boards of desired thickness. For thickness greater than 6 mm, bamboo mats can be interleaved with wood veneers. Specially designed platens (matching dies) are used for making BMCS and moulded articles. A generalized process flow chart is given in Fig. 1.

3.2. Product development

3.2.1. Bamboo mat board. Use of any new material depends upon its suitability for various applications *vis-à-vis* the materials already in use. Development of appropriate application technology plays an important role in acceptance of any new material. BMB is essentially a layered composite comprising several layers

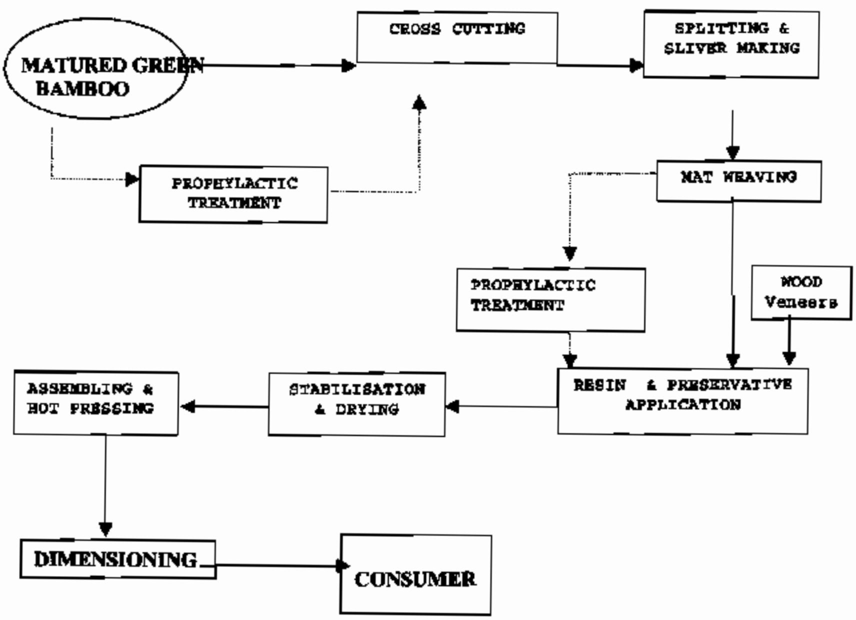

Figure 1. Generalized process flow-chart for bamboo mat-based composites.

of woven mats having excellent internal bond strength, and are resistant to decay, insects and termite attack. They have physical and mechanical properties at par with waterproof plywood and are fire resistant. Their mechanical properties depend upon the material used for making mats, i.e. bamboo slivers, the weaving pattern and the adhesive used for bonding.

Table 1 gives the strength properties of BMB made from some bamboo species as studied at the Institute under the project 'Wood Substitute (India)' [15] sponsored by IDRC, Canada. Unlike plywood that has cross-grain layers, BMB has mats with herringbone weaving pattern arranged in the same direction with respect to weave pattern. Stresses (tensile and compressive) applied along the length and width of the board will be at an angle of 45° to the grain direction of the slivers. For this reason, the strength of BMB in tension will be lower than the strength of round bamboo along the length. It is for the same reason that tensile strength, modulus of rupture (MOR) and modulus of elasticity (MOE) of BMB is lower compared to that of structural plywood or wood (Table 2). It can also be seen from the Table 2 that the specific strength in bending (MOR/ρ^2, where ρ is the specific gravity) and load-bearing capacity in deflection (MOE/ρ^3) of BMB is lower than that for plywood or wood, which is understandable from the fact that the specific gravity of BMB is comparable to that of plywood and wood. However, it has been observed that strength of BMB in tension or bending at an angle of 45° to the length or the width of the board is also higher than the corresponding strength along or across the board length. Thus, it can be inferred that the strength and stiffness of BMB is related to the weaving pattern of the mats.

However, modulus of rigidity (MORg) or shear modulus of BMB in the plane of the board is very high and is comparable to the required values for structural plywood as per Indian Specifications IS: 10701. It is interesting to note that MORg

Table 1.
Physical and mechanical properties of BMB from some Indian bamboo species

Property	Bamboo species [Average (standard deviation)]				
	Requirement of IS: 13598-1994	*Ochlandra travancorica*	*Meloccana bambusoides*	*Bambusa bambose*	*Dendrocalamus strictus*
Density (kg/m^3)	500–900	770 (62)	700 (65)	890 (75)	800 (74)
Internal strength (N/mm^2)					
Dry state	0.70	2.11 (0.24)	2.42 (0.26)	1.33 (0.11)	1.86 (0.16)
Wet state	0.50	1.97 (0.20)	2.14 (0.22)	1.10 (0.11)	1.42 (0.15)
Surface strength (N/mm^2)					
Dry state	4.5	11.50 (1.62)	11.23 (1.50)	8.06 (0.80)	11.20 (1.30)
Wet state	3.0	11.40 (1.75)	10.47 (1.45)	6.05 (0.60)	8.40 (0.90)

Table 2.
Comparative mechanical properties of BMB, structural plywood and eucalyptus wood

Material	Specific gravity (ρ)	Tensile strength (N/mm^2)	Modulus of rupture (MOR) (N/mm^2)	MOR (ρ^2)	Modulus of elasticity (MOE) (N/mm^2)	MOE (ρ^3)	Modulus of rigidity (MORg) (N/mm^2)
BMB (3-layered)	0.75	22.7 (2.6)	50.7 (5.6)	90	3670 (400)	8700	5870 (695)
Structural plywood*	0.55						495 (75)
– along the grain		32.7 (6.6)	47.7 (8.6)	158	5690 (685)	34200	
– across the grain		33.8 (6.4)	30.0 (4.8)		2560 (385)		
Silver oak wood	0.53	51.5 (6.7)	61.5(2.8)	215	8100 (800)	54400	485 (48)

*Made from *Grewelia robusta* (silver oak). (Figures in parentheses represent the standard deviation.)

Table 3.
Potential applications of BMB and BMVC

Sector	Applications
Housing	Doors, partitions, paneling, cladding, concrete shuttering, roofing, ceiling and structural uses
Packaging	Packing cases for horticultural products like apple and mango, tea-chest boxes, tobacco packaging cases, ammunition boxes
Storage and transport	Grain storage bins (internal and external), cover for bullock carts and horse/mule drawn carriages
Furniture	Tables, cots, divans in combination with wood

of BMB far exceeds that of both structural plywood and wood. This is attributable to the herringbone weave pattern. The ratio of MORg to MOE, which is around 0.6 for wood, and 0.08–0.15 for plywood, exceeds 1.5 in the case of BMB. Clearly, BMB has high in-plane rigidity and hence high racking strength and is more flexible than equivalent plywood. This property of BMB can be advantageously used in many engineering applications. In fact BMB has been found to be especially useful as sheathing material in structural and semi structural uses such as walling, partitions, roof sheeting [16], door skins, box furniture, built up hollow beams, gussets, containers [17]. Table 3 and Figs 4–9 show some typical end use applications of BMB.

Investigations have also been undertaken at the IPIRTI regarding suitability of BMB for manufacture of secondary parts of aircraft and gliders as substitute for speciality plywood made from *Dysoxylum malabaricum* and *Palaquim ellipticum*. BMB meet all the requirements prescribed in the relevant Indian specifications and have in fact much higher cross sectional shear strength compared to plywood [18].

3.2.2. Bamboo mat veneer composite. In BMVC, wood veneers are placed in-between the layers of bamboo mats. The properties of BMVC depend upon the

Table 4.
Physical and mchanical properties of BMVC

Sl. No.	Property		Structural plywood	BMVC* 21 mm	Plywood**
1	Density	(kg/m^3)	750	800 (81.5)	553 (56.5)
2	Strength	(N/mm^2)			
(a)	Tensile				
	Along the grain		54	36.4 (6.5)	32.7 (6.6)
	Across the grain		34	35.8 (6.4)	33.8 (6.4)
(b)	Compressive				
	Along the grain		34	43.9 (6.2)	24.5 (2.8)
	Across the grain		29	40.2 (6.0)	20.5 (2.6)
3	Modulus of rupture	(N/mm^2)			
	Along the grain		49	68.5 (7.8)	47.7 (8.6)
	Across the grain		29	55.4 (6.6)	30.0 (4.8)
4	Modulus of elasticity	(N/mm^2)			
	Along the grain		7355	7820 (850)	5690 (685)
	Across the grain		3923	3210 (485)	2560 (385)
5	Modulus of rigidity	(N/mm^2)	588	3315 (505)	495 (75)

*67% *Grewelia robusta* (silver oak) veneers and 33% bamboo mats.
**7 ply, 16 mm made of silver oak veneers.

mechanical properties of wood veneers that are placed in between bamboo mat layers, in addition to the properties of the bamboo mats and the adhesives used in bonding. Investigations have shown that strength of a panel made by plantation timber is substantially enhanced when made in combination with bamboo mats. MOE and MOR of BMVC are higher than equivalent plywood and this depends on the number of layers of veneers for a given thickness of BMVC (Table 4). Due to the presence of woven bamboo mats, BMVC has different mechanical properties along and across the length of the board. The properties are comparable to that of structural plywood. Hence, for all practical purposes BMVC can be used in a similar way to plywood for structural applications. As BMVC will be economical in higher thickness as compared to BMB, BMVC may be advantageously used in place of structural plywood.

Figure 2 depicts bar charts showing MOR, MOE, and MORg of BMB (both herringbone and rectangular weaving patterns), BMVC (comprising 67% silver oak veneers and 33% bamboo mat), and structural plywood (silver oak) along with standard deviations.

3.2.3. Bamboo mat corrugated sheets. Roofing materials such as asbestos cement corrugated sheeting (ACCS), corrugated fiber reinforced plastics (CFRPs), corrugated aluminum sheeting (CAS), corrugated galvanized iron sheeting (CGIS), which have been established for more than several decades, are being subjected to scientific scrutiny on several counts, including their impact on workers' health and

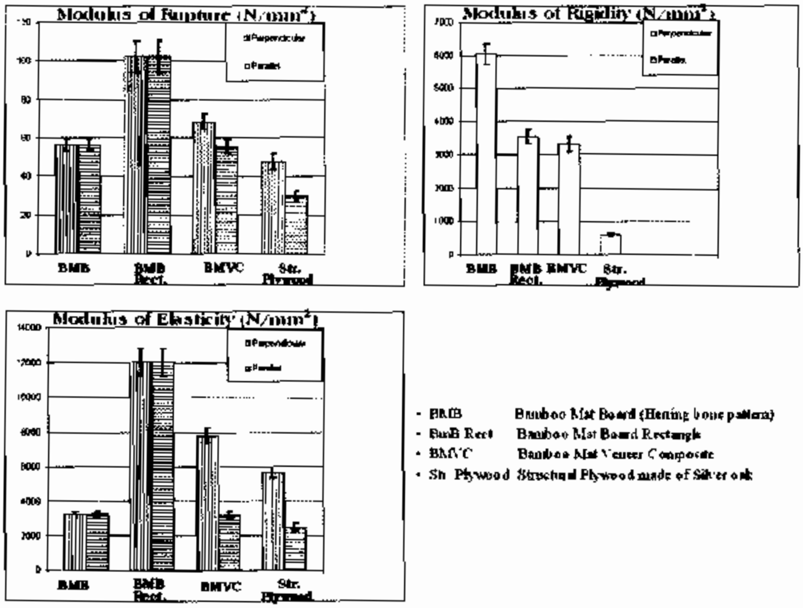

Figure 2. Comparative strengths of BMB, BMVC and structural plywood.

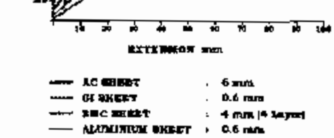

Figure 3. Comparative load–deflection curves for BMCS, CGIS, ACCS and CAS.

environment, the energy requirement for their manufacture, and sustainable supply of raw materials. Of late, priority is being given, and rightly so, to 'green' building materials, based on renewable resources. Scaling-up of the pilot scale technology for its industrial adoption is in progress under a project funded by the Ministry of Environment and Forests, Government of India. The shape and area under the load–deflection curves (Fig. 3) of various corrugated roofing materials, namely, BMCS, ACCS, CGIS, and CAS, clearly bring out the comparative advantage of BMCS over other corrugated materials.

3.3. Product standardization

Standardization of procedures for testing any material is a *sine qua non* to build up consumer confidence and quality monitoring. Although bamboo mat composites are similar to veneer plywood, conventional methods of testing strength properties prescribed for plywood cannot be applied to these due to criss-cross sliver construction. Therefore, separate test procedures for BMB have been evolved based upon the methods specified for determining internal bond (IB) strength and surface strength (SS) in IS: 2380. The Bureau of Indian Standards, the national standards body, has already brought out the specification for BMB [19] and BMVC [20].

3.4. Economic feasibility of BMB production and extent of technology adoption

A techno-economic feasibility study of BMB manufacturing technology developed at IPIRTI under IDRC sponsored project Bamboo Mat Board (India) was conducted by the Institute in 1992 in collaboration with Institute of Socio-economic Change, Bangalore. According to this study the benefit cost ratio to be 1.4 at 15% discount rate [21]. In 1997, an independent evaluation of BMB technology was conducted by the Agricultural Finance Corporation, Mumbai, India that has also found the technology to be technically feasible and economically viable. According to this study, a BMB unit with an annual production capacity of 129 000 boards (per shift) of about 3 square meters and 3 mm thickness, requires capital investment of Rs. 16.85 million (US$ 0.38 million) and recurring expenses of Rs. 27.31 million (US$ 0.62 million). Keeping the sale price at 20% lower than that of equivalent plywood for market promotion, BC (benefit cost) ratio works out to 1.29 at 19% discount rate. Such a factory is likely to generate about 0.20 million person-days, mainly in mat weaving. It is estimated that if 25% of present plywood consumption of 800 000 m^3 were replaced with BMB, it would result in saving 8000 ha of forests while generating employment to the tune of 35 million person-days particularly for rural/tribal women.

With regard to the cost–benefit analysis, if one looks at the investment and the number of jobs created, it is revealed that there are not many other industrial activities that provide so many jobs at such low investments. Three factories in India, one each in the public, private and NGO sectors, are regularly producing BMB. Two more industries in the private sector are being established for which IPIRTI is providing the technology. The computed production capacity of the five units will be around two million square meters of BMB per eight hour shift.

BMCSs produced at the pilot facility established at IPIRTI have been used in several demonstration structures as mentioned above and establishment of an industry is planned under a project funded by the Ministry of Environment and Forests, Government of India.

Some important advantages of adoption of bamboo mat based technologies are

1. Reduced dependence on natural forests through wood substitution, thereby contributing to protection of environment.

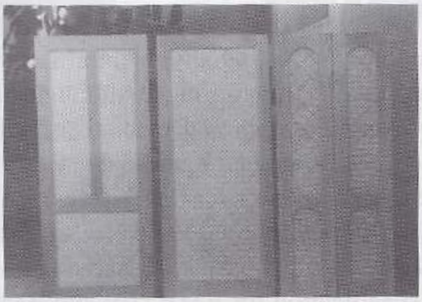

Figure 4. Panel door with BMB as panel inserts.

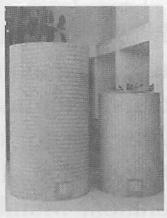

Figure 5. Grain storage bins made from BMB.

Figure 6. BMB-based curved roof.

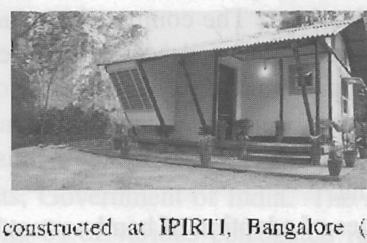

Figure 7. Bamboo house constructed at IPIRTI, Bangalore (March 2001) using BMB for door/window shutters and BMCS for roofing (in collaboration with TRADA Tech., UK under a DFID funded project).

2. Creation of employment opportunities, particularly for rural/tribal women.
3. Improvement of skills of people and enhanced earning capacity, leading to overall welfare of society and particularly the economically weaker sections.
4. Bamboo is a very fast growing species and is suitable for rehabilitation of degraded forest, other waste lands and shifting cultivated areas.

4. CONCLUSIONS

The BMB technology has attracted attention of a number of entrepreneurs and few industries have already been set up in the country. However, positive policy and technological initiatives are necessary to accelerate the use of bamboo mat composites including encouraging their use in public sector where currently wood is banned; development of application techniques for various end products; and evolution of code particularly in housing, construction, transport; dissemination of information about their utility through demonstration and exhibitions.

Considering the vast social and environmental implications and employment potential, a policy thrust at national level is necessary for development of bamboo resources in general and promotion of bamboo composites in particular. As a first step, Government has already given a favourable push by exempting bamboo composites from excise duty. Eco-labeling of the products will also help promote exports.

Every new technology for producing intermediate material requiring further processing to manufacture end products requires continued R&D support during its commercialization to solve problems which may come up during transfer of technology from lab to factory. The technologies for BMB, BMVC, BMCS and bamboo-based housing are no exception to this. In fact, they need such support even more due to natural variation in the characteristics of the main raw material, bamboo, associated with different species available in different areas/regions, and different level of skills in bamboo mat weaving in various tribal/rural groups traditionally weaving mats.

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