BIVALVE MOLLUSKS SHELLS VALORISATION AND RECYCLING: MARKET POTENTIALITY AND NOVEL BUILDING PRODUCTS

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Abstract - Construction is a fundamental driver of the world economy, recognized as a sector that generates a great contribution to the social and economic development. At the same time, it shows an enormous environmental impact through an unstoppable consumption of non-renewable resources, a high energy consumption, and an associated atmospheric emission of pollutant. Consequently, the research and development of novel and green production processes and sustainable building materials is of paramount importance. The sustainability of materials and production processes could be improved by enhancing and reusing wastes from various industrial sectors. In this paper, the fishery sector will be analysed, considering its derived wastes as secondary raw materials with interesting drawbacks into the construction sector. The fish sector, in the broadest sense (breeding, production, manufacturing, catering, etc.), generates a large number of wastes that could generate a significant environmental impact and a rather high disposal costs, both in economic and environmental terms. This paper will analyse the most traded shellfish market, focusing on mussels, clams, and oysters, examining their production processes and estimating the possible amount of available waste. Finally, on the basis of scientific literature and commercial info graphics, the construction products currently available on the market and under development will be discussed.

Keywords - Mollusk Shells, Valorization & Recycle, Novel Building Materials, Building Products, Circular Economy.

I. INTRODUCTION

The recent trend in the construction industry is using alternative sources for construction and building materials manufacturing, which can replace virgin materials in order to reduce the environmental impact in terms of energy consumption, pollution, waste disposal, and global warming. Without a proper waste recycling, the current huge quantity of industrial by-products and waste would be burned or land filled, procedures that could cause severe environmental pollution and/or contamination.

A recently significant regulation is the Minimum Environmental Criteria (MEC) [1] which states a minimum content of recovered or recycled material into building materials manufacturing, equal to at least 15% by weight evaluated on the total of all materials used. For this purpose, this paper aims to discuss possible reuses and valorisation of wastes from the fishing industry, in particular shells, as inert materials for construction. Nowadays, the management of such wastes, derived from the food industry, represents a significant global problem; therefore, providing an alternative solution for a more sustainable disposal compared to the common landfill or sea transfer procedure allows to respect the environment by avoiding the generation of waste.

The rapid growth of the world population has led to an exponential increase in the demand for various food and energy resources. This ever-increasing demand has accelerated the industrialization and modernization of agri-food industries, increasing their diversity in production and improving the quality and quantity of their products. An unintended consequence of such development has been the production of huge quantities of agri-industrial wastes, which are usually landfilled, due to the high cost associated with their treatment to reduce the organic load from both industries and households (waste urban

solids). It has been estimated that the volume of food waste generated on a global scale amounts to about 1.3-1.4 million tonnes and will reach 2.6 million tonnes by 2025 [2]. Every year, in fact, the global industrial activities generate an enormous amount of waste, causing enormous problems in treatment and disposal, as well as economic losses and emissions of pollutants into the atmosphere.

Consequently, it is necessary to develop new greener and more sustainable manufacturing processes, materials and products, also exploiting the reuse and recycling of wastes. The only practical way to reverse the current situation and improve the circular economy is to design sustainable production processes and to follow an accurate life cycle management [3].

II. REUSING AGRI-FOOD WASTES TO IMPROVE THE CIRCULAR ECONOMY IN CONSTRUCTION

Worldwide, with a greater interest for sustainability, boosted by the worrying continuous warning on worlds issues such as climate changes, disasters, epidemics, atmospheric pollution and health related problems, renewable resources are becoming the solution key, especially in the research and development of green materials and technologies.

The construction sector is increasingly concentrating into an innovative design, greener, more sustainable and more responsive to the surrounding environment. That is slowly leading to a smart, self-adaptive and self-sufficient construction whose energy needs are slowly decreasing making the entire sector less dependent from fossil carbon exploitation for the energy production.

Accordingly, an increasing number of studies, either from academia and other public entities, as well as industries, are focusing in developing sustainable construction and building materials reusing wastes. The ultimate trends are implementing the reuse of natural non-harmful wastes to gain a complete end-of-life cycle of products and components.

Indeed, the possibility of continuous recycling of discarded products, or even the opportunity to compost them, or in any case safely landfill without the aid of costly and environmentally hazardous treatments, at the moment seems the focus of the international debate.

Among those, agri-food by-products and wastes reuse shows great potentialities for the construction industry. Many are the already studied wastes: corn cob ash [4], oil palm shell [5], rice husk ash [6], bamboo leaf ash [7], periwinkle and cockle shell [8], coconut shell [9], vegetable fibres [10], almond shell [11], spent coffee ground [12], etc. These are only some examples of the variety of studies that have recently been conducted.

III. MOLLUSKS SHELL REUSE: A VIABLE OPPORTUNITY

3.1. Mollusks market: procedure, types, and derived wastes

Mollusks' waste derives from three sectors: (a) fishing and breeding, (b) processing, (c) trade and consumption. The mollusks production process takes place through a series of phases that start from the wild seed sourcing, to the growth of the mollusks, to the packaging and marketing of the final food products. From the study of the processing phases it is possible to estimate the type and quantity of waste deriving from the selection and processing phases, during which the mollusks unsuitable for sale are eliminated.

3.2. Manufacturing process

The bivalve mollusks production chain requires a quite laborious and complex process, which generally lasts from 8 to 12 months. Some phases of the production chain are shown in figure 1. The process starts with the breeding or harvesting of the different species in the production areas (figure 1A). These can be part of the sea, lagoon or estuary, where there are natural banks of bivalve mollusks or places used for their cultivation.

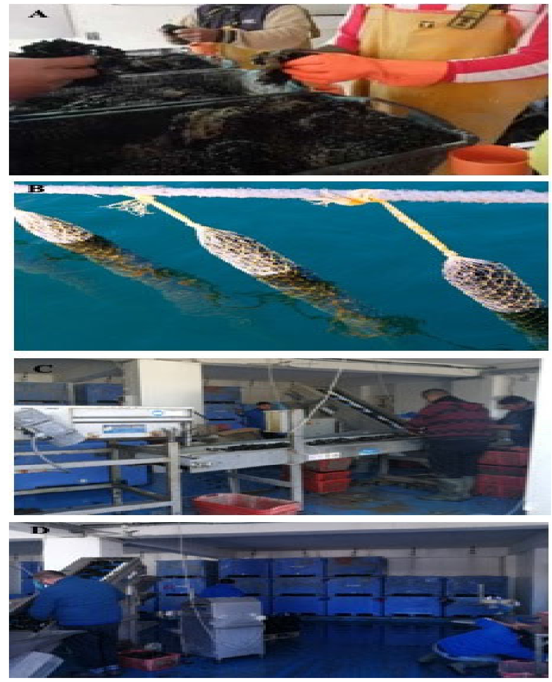

Fig.1. Seed insertion (A), mollusks rests immersed into water (B) (source: https://cozzadicervia.com/cooperativa/cosa-facciamo/). Mollusks selection and processing with conveyor belt (C) and shellfish purification in tanks with water jets (D).

The phases of the proper production process begin with the finding of the wild seed and the pressing of the seeds, i.e. the insertion of these inside socks, also called "rests", i.e. tubular polypropylene nets, immersed in the sea, to which a buoy is fixed being the element that will allow the row to remain properly suspended (figure 1B). After 2 or 3 months from the immersion, the re-tightening operation takes place, i.e. the remains are hoisted on board the ship and the sock is changed according to the mollusks growth. Upon reaching the commercial maturity, the bivalves are definitively hoisted on board and the ginning, selection (figure 1C), processing and purification phases take place (figure 1D). Finally, the product is packaged and is ready to be sold on the market.

3.3. Most traded types of bivalve mollusks: market analysis

The three most commercialized bivalve mollusks species in Europe are mussel, clam, and oyster (figure 2), that represent about the 98% of the volume and value of the total production of bivalve mollusks market [13].From 2010 to 2019, the global mollusks production increased by 16%, mainly due to Chinese production growth. In 2019 China, Chile and Spain resulted the worldwide top three producers, accounting for 72% of global production. In 2019, the world mussells production reached about 2 million tonnes [14]. In contrast, the total oyster production in 2019 was estimated at around 134,000 tonnes. As a result, from 2010 to 2019, global oyster production increased by 40%, mainly due to Chinese production, which supplied 85% of world production in 2019. Other major global producers include, to a lesser extent, Republic of Korea and the United States of America [15].Mollusks are an important resource for the marine food chain and have a significant impact on the marine environment because they are "filtering" animals. Indeed, they assimilate the food dissolved in the water through siphons, which with internal and external movement effectively filter the waters they live in. As a result, the waters are continuously purified through this filtering process. Hence, mollusks actively contribute to the marine environment general health. The class of bivalves belongs to the phylum Mutili, so named for the presence of two valves, connected by an elastic ligament located on the dorsal margin of the shell, that are made of calcareous materials, mainly calcium carbonate, which surround the animal's body. Most bivalves live near the seashore, although there are some species that live in the depths of the ocean, even reaching more than 5,000 m in depth. The bivalves, therefore, persist on the bottom and in the substrate of fresh lakes or river waters, giving rise to dense populations [16].In the following sections, the mussels, clams and oysters' markets are examined, with data reported for the main producing countries; therefore, figures 3 A-B-C show the production trend respectively for Spain, Italy and France.

Fig. 2. Types of most European traded bivalve mollusks: mussels (A), clams (B) and oysters (C).

3.3.1. Mussel

Each year, the mussel represents over two-thirds of total aquaculture production, making it the most farmed species in the EU. After recording a decline from 2017 to 2018, mussel production in 2019 increased by 2% in volume and 7% in value compared to the previous year, reaching 487,662 tonnes and €451 million. The increase in value was fueled by the growth in France, where the production increased by 23% in volume, to around 60,255 tonnes, and by 32% in value, to around €134 million.In Italy, another country that has contributed to the production volumes increase, 72,450 tonnes of mussels were farmed for a total value of €54 million. Spain (figure 3A) and Italy mainly produce the Mediterranean mussel Mytilusgalloprovincialis: in 2019, the average price of the mussel in these two countries was 0.52 EUR/kg and 0.75 EUR/kg, respectively. In France, on the other hand, more valuable mussels of the Mytilus edulis species are produced, i.e. blue or Atlantic mussels, which in 2019 had an average price of 2.22 EUR/kg [15].

3.3.2. Clams

In 2019, the clams EU production fell by 19% compared to 2018, reaching 32,428 tonnes, which represents the lowest amount of the decade under analysis. Both Italy (the largest producer) (figure 3B) and Portugal (following at a distance) were responsible for this trend. The Italian production fell to 27,160 tonnes, down 13% compared to 2018, for a total value of €136 million, down 15%. In Portugal, the production of clams halved to 2,027 tonnes and €33 million. The price of these species in the two countries is very different: in 2019, in Italy it was 5.02 EUR/kg, 3% less than in 2018, while in Portugal it was 16.31 EUR/kg, 33% less compared to 2018. This price difference could be due to the fact that the clams farmed in the two countries belong to two different species: in Italy the Ruditapesphilippinarum species is mainly farmed, and in Portugal the Ruditapesdecussatus species is more diffuse [15].

3.3.3. Oyster

In 2019, the EU farmed 101,879 tonnes of oysters for a total value of €463 million. Compared to 2018, this represented a 7% decrease in volume and a 2% increase in value. The cupped oyster (Crassostreagigas) is by far the most farmed species in the EU. Almost 85% of EU oyster production takes place in France (figure 3C). After three years of growth, in 2019 French production fell by 8% compared to 2018, reaching 85,947 tons. This decrease was probably due to the presence of the Norovirus (the gastroenteritis virus) in some production areas in December 2019, which led to the ban on the sale of this product. In 2019, the average price of oysters in France was 4.63 EUR/kg, i.e. 13% more than in 2018, and the total value of production stood at €398 million, +5% compared to 2018 [15].

IV. THE BIVALVE SHELL MARKET: FROM WASTE PRODUCTION TO RESOURCE

In general, the cultivation of mollusks in Italy is directed towards the breeding of two main species: mussels (Mytilusgalloprovincialis) and clams (Tapes philippinarum); only in recent years there has been a small oyster's production (Crassostreagigas).

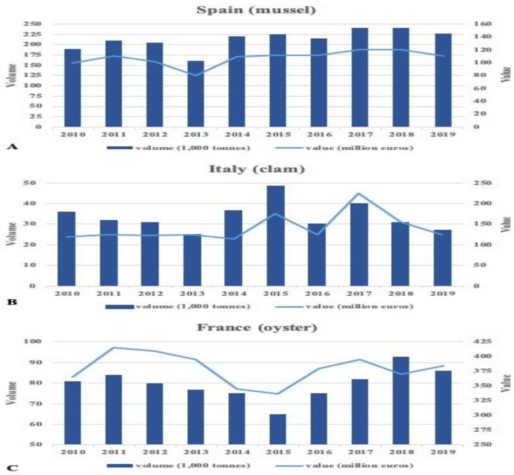

Fig. 3. Most diffuse bivalve aquaculture production in Spain (A), Italy (B), and France (C).

However, a production increase inevitably corresponds to a consequent large amount of waste mainly in the form of shells, which can represent up to 90% of the weight of fresh mollusks. Nowadays, shells show a very little use and are commonly considered as waste. Hence, they are often landfilled or discarded into the sea, causing a significant level of environmental concern, and resulting in the loss of valuable natural resources. The bivalve mollusks shells are mainly constituted of calcium carbonate (CaCO3), showing the potential to become a promising secondary raw material for several applications in construction [17], in light of the circular economy approach. Generally speaking, over 10 million tonnes of bivalve shells are generated each year, representing a large volume of pre- and post-consumer waste that usually represents about the 60-90% of the live weight depending on the species. Shell wastes is a major problem for the shellfish producers, sellers and consumers, both in practice and economically. Shell heaps are frequent worldwide due to unregulated disposal procedures, causing environmental damage in terms of badodours and contamination, caused by the organic matter decomposition along with a visual pollution [18]. Shells, as the main by-product of shellfish culture, can find a legitimate place in this paradigm in various ways, regardless of the waste producers, i.e. shellfish farmers and/or processors, restaurateurs or consumers. For example, in EU, mussels and clams are usually sold and served with their shells, whole or processed, canned or frozen without their shells; while oysters are commonly supplied to restaurants with their shells full and half eaten. In contrast, in Asia, shellfish are generally processed and most of the shells are removed upon collection and regularly disposed of in the oceans or along the coasts [19].

4.1. Waste treatment

The fishing industry includes any sector or direct activity related to the fishing, farming, processing, preservation, storage, transport, and marketing of fish or fish products. All these activities can be summarized in three large sequential macro-categories: commercial fishing and the fish breeding, mollusks and crustaceans (aquaculture and fish farming), the fish processing sector for the production of fish products, and finally the fish products trade, from markets to large-scale distribution. These categories generate a large number of Animal By-Products (ABPs), which are materials obtained from animals which are not intended for human consumption, including mussel shells unfit for human consumption due to manufacturing defects, packaging or exceeding of shelf life. The management and treatment of ABPs are governed by the European Regulation 1069/2009/CE [20]. European legislation establishes the health standards applicable to the stages of collection, transport, storage, handling, transformation and disposal or possible recovery of by-products of animal origin, in order to avoid any risk to public health and animal health as well as to protect the safety of the food and feed chain [21]. ABPs are divided into three specific categories that reflect their level of risk to public health:

- Category 1: all parts of animals suspected of being affected by BSE (bovine spongiform encephalopathy) or which are to be killed for BSE eradication; pets, zoo and circus animals; wild animals suspected of being infected with diseases transmissible to humans;
- Category 2: all by-products other than category 1 and products of animal origin containing drug residues or contaminated agents beyond the Community limits; the manure and the contents of the digestive tract;
- Category 3: all by-products deriving from animals fit for human consumption but not intended for it for commercial reasons or processing problems or packaging defects or because they are out of date.

Different uses or disposal destinations correspond to each risk category. Mollusk shells belong the third category being by-products deriving from the manufacture of food products, which for commercial reasons are no longer intended for consumption. However, the regulation does not apply in the event that the shells of the mollusks are deprived of the soft tissues and of the meat of the mollusks themselves which, according to the European regulation, must be disposed of into authorized landfills.As regards the separate collection that regulates the various municipalities in waste management, it should be emphasized that mollusks shells cannot be disposed of into the usual organic waste, since it is aimed at the production of compost for fertilizer. In fact, the shells of bivalve mollusks, being mostly composed of calcium carbonate, have an inorganic nature and a calcareous composition; therefore, they do not possess the necessary characteristics to be considered compostable. Therefore, having a long decomposition time, they must be disposed of in the undifferentiated waste, even if this practice is harmful to the environment and is a waste of recyclable biomass.Furthermore, after carrying out a market survey regarding waste management and collecting data, it was possible to estimate the cost of disposing of mollusks shells. It can be considered as an average price, 15-18 cents/kg. The final cost of disposal, however, depends on the location of the waste itself; to which the cost of transportation must be necessarily added.

V. MOLLUSKS SHELL REUSE IN CONSTRUCTION

To date, analysing the state of the art on effective ways to recycle waste various applications are present ranging from agriculture, breeding, purification, to the manufacture of increasingly eco-sustainable building materials.

5.1. Scientific studies

In the construction field, this theme is currently evolving; in fact, many experimental studies have been conducted on the reuse of mollusk shells for the purpose of developing novel building materials [22]. A fundamental and preventive phase for the mollusk shells reuse is an adequate pre-treatment aimed at eliminating impurities and residues of any organic nature (animal remains, algae, incrustations of various natures, etc.). This generally consists of washing, calcining and crushing to the desired size. As shells are considered as waste, their proper handling and treatment must be undertaken before they are incorporated into the final material, to ensure the complete impurities removal. In addition, a proper crushing is required to ensure a better bond between the shell aggregate and the binder. Wide reuse of shells has already been tested in mortars and conglomerates. What clearly appears is that the most of the studies are quite recent meaning that the reuse of see shells is quite an innovative topic with a lot of research needed. Bamigboye G. et al. [23] evaluated the effects of recycling saltwater clam shells (Seniliasenilis) partially or totally replaced as coarse aggregate in green concrete production. The aim was to identify the relationships between the quantities of shells added to the mortars, the slurry workability, and the mechanical strength. Furthermore, the shell waste recycling for the construction of green buildings is to be encouraged, as it offers economic benefits and improved environmental prospects. In fact, the results obtained from this experimental work are expected to offer an alternative method for an ecological production of concrete.Similarly, Chen D. et al. [24] evaluated the physical and mechanical properties of mortars containing crushed oyster shells. The mixtures were prepared by replacing in different percentages the river sand with crushed oyster shells with the aim of studying the behavior of these novel mortars with those produced with traditional aggregates. Among the main results, the use of oyster waste in the production of cement mortars improved the cost efficiency of the material production and made it more sustainable than the traditional mortars' one.Li H.Y. et al. [25] published a study in which fine aggregates, which are normally used in the production of lightweight red bricks, were replaced with different percentages of ground oyster shells, in order to test their engineering properties. Currently, the Kinmen County (China), imports huge quantities of red bricks for applications as partition walls between old and new buildings. Producing those bricks locally reusing wastes deriving from fishing would reduce both the environmental impact, given by the incorrect disposal of such waste, and the carbon footprint caused by the imported building materials.Ibrahim A.S. et al. [26], on the other hand, were concerned with optimizing the properties of cement by using marine shells as organic waste, adding them to fine aggregates according to different percentages. In fact, marine shells have a chemical composition similar to limestone-type aggregates, and also contain traces of chloride and sulphate salts which give concrete active properties, increasing its mechanical resistance.Finally, Ramírez E.W.G. et al. [27] evaluated the properties that fan-shaped shell waste, crushed to reach a particle size ≤0.063 mm (filler) could confer on the cement with the aim of evaluating the behavior of the concrete, both in the fresh and hardened states, in order to improve the mechanical and physical properties, obtaining a more sustainable concrete.

5.2. Building products

Many are the shell-based building products that are already available on the market. Following, some commercial products are reported with the main description and characteristics.

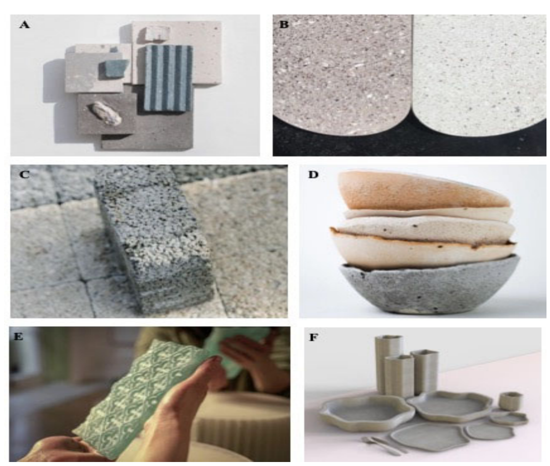

Fig. 4. Commercial product already available on the market: Sea Stone (A), Shellcrete (B), Eco-Pavé (C), Plâtre de mer (D), Thames Glass (E), Ostra (F).

Sea Stone (figure 4A) by Newtab-22 [28], a design studio specialized in natural and new materials based in Seoul and London, proposes the use of oyster shells to manufacture an environmentally and economically sustainable material to be used for tiles. The production method is currently done manually to avoid the use of heat, electrical and chemical treatments and to ensure that the process is as sustainable and cost effective as possible. The waste shells derive from fish industries and, once collected, they are washed, grounded and finally mixed with various natural binders to develop decorative tiles for interiors and exteriors as well as for interior products such as mirrors, wall decorations, etc. Shellcrete (figure 4B), manufactured by Local Works Studio [29], is an ongoing project that transforms shell wastes from fishing and catering into materials useful for both architectural and landscaping applications. In 2018 the Shellcrete project was funded by the EU to develop an exterior cladding material for buildings using 100% waste materials. The company sourced oyster shells as waste in restaurants and mixed them with other waste materials, creating a palette of self-coloured grouts to be poured as weatherproof exterior tiles. Local Works Studio continues to design cladding materials for tile, plaster, brick, mortar, paint and other surface coatings and finishes.Eco-Pavé (figure 4C) was born from an idea within the Research Department of the ESITC Caen of the University of Épron (France) [30] for the production of artificial pebbles, a typical external paving of the area. Given the scarcity of available raw materials, they were replaced by mussel waste, a common resource in this coastal region, with a quantity of recycled aggregates up to 40%. The use of shells not only preserves local natural resources but also allows water to naturally infiltrate the soil. The production [31] is the responsibility of three local companies for the shells crushing, for the manufacture of artificial stones and for the manufacture of a user guide, intended for its industrial production and development. This has also contributed to the improvement of the local economy.Plâtre de mer (figure 4D) experimented by the Atelier Lucile Viaud [32] is, literally, a "marine plaster" made up of shells of mollusks collected and processed in Brittany (oysters, mussels, abalones, quills, etc.). Entirely biodegradable and recyclable, it is available in as many colors as there are species of by-products available in the region depending on the season. The mineral of the shell is reflected in its soft texture and smell.The London architectural firm, Bureau de Change [33], has produced a range of patterned tiles using Thames Glass (figure 4E), a biomaterial created by the artist Lulu Harrison from mussel shells. Harrison creates this bio-glass using ground mussel shells in combination with local sand and waste wood ash. The Bureau de Change was also involved to explore whether this material could be used to create an environmentally friendly cladding for buildings. Together, they created a series of 3D molded cast glass facade tiles with a variety of decorative motifs, referencing mid-19th cent. terracotta chimney pots created by ceramics manufacturer Royal Doulton. The team speculates that the glass cladding tiles could be used in future building design. Ostra (figure 4F) is a range of crockery created by Jade Echard [34] using an innovative material similar to ceramics but obtained from oyster shells. Echard is developing the material in the laboratories of the Queen Mary Institute of Dentistry in London in collaboration with Dr. Michael Cattell, dental technology specialist in biomaterials. Ostra is an alternative material and system for critically engaging with the entire supply chain. The project engages with local communities, creating a network of people around oyster shells, such as oyster farmers, restaurants, scientists and designers, reducing the pollution burden on the environment, production and transportation costs.

VI. CONCLUSION

This study has paid attention to the fishing industry which actually offers a large amount of waste material, currently unexploited, which is traditionally disposed of into landfills or dispersed into the sea, resulting in polluting activities for the environment and the humans. Hence the need to find alternative solutions. In particular, effective sustainability perspectives have been outlined, to enhance the waste reuse deriving from the fishing industry in the perspective of the circular economy, providing the basis for further research and development of novel building and construction materials in order to improve the sustainability of the sector, today rather lacking and looking for effective solutions. The proposed study, therefore, is aimed to provide an input for raising awareness of the community with respect to the use of new innovative systems and materials.

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