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Case study of Life Cycle Assessment and sustainable business model for sea urchin waste

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ABSTRACT

Climate change and the accumulation of waste are major challenges facing the world in the 21st century and have substantial impacts on the environment. The Food and Agriculture Organization (FAO) estimates that food waste amounts to 1.3 billion tonnes per year. This study aims to explore the potential for reusing sea urchin waste to develop eco-sustainable products. A sustainable business model based on the environmental benefits of sea urchin exoskeleton waste is presented as an example. The powder, which can serve as a calcium supplement for laying hens, is evaluated using Life Cycle Assessment (LCA) and two different scenarios are considered. The results of the LCA analysis show that the Alternative scenario, which involves the reuse of sea urchin waste, has significantly lower negative impacts compared to the Baseline scenario, based on disposal of the organic fraction of municipal solid waste (ORMSW). Although the sea urchin market is niche, the potential benefits from its waste are countless. The LCA-based approach and sustainable business model demonstrate the feasibility of creating new eco-sustainable products from sea urchin waste.

1. Introduction

Climate change is one of the biggest issues of the 21st century and is having a large-scale impact on both human and natural systems. According to the last publication of the Intergovernmental Panel on Climate Change (IPCC), the Sixth Assessment Report (AR6) in 2022, the human influence on the climate system has been found to be the major cause of the observed global warming since 1950s (Pörtner et al., 2022). Currently, the anthropogenic greenhouse gas (GHG) emissions, mainly carbon dioxide (CO_2), methane (CH_4) and nitrous oxide (N_2O), are at the highest levels ever recorded. These physical elements are considered to be the main contributors to climate change. In particular, around half of the CO_2 emissions from 1750 to 2011 were released in the last 40 years, mainly from the use of fossil fuels in the key sectors of our modern economy, such as energy supply (electricity and heat production), transport, industry, agriculture, land use and fishery. As a result, the increased concentration of GHGs in the atmosphere has caused higher energy retention, leading to a rise in global temperature. These phenomena have caused shifts in terrestrial, marine, and freshwater species, resulting in new migration patterns and species interactions. Moreover, another important issue related to environmental damages is waste generation.

Every year, the global organic municipal solid waste (ORMSW) amounts to 2.01 billion tonnes (Kaza et al., 2018). At least 33% of this waste is not managed in an environmentally safe manner (Kaza et al., 2018). Indeed, it is estimated that 1.6 billion tonnes of greenhouse gases, which is equivalent to 5% of global emissions, are generated from the volume, composition, and management of ORMSW (Kaza et al., 2018). The most significant components of ORMSW are primarily plastic, paper, and food. According to FAO estimates, around 1.3 billion tonnes of food are lost or discarded each year, amounting to one-third of all edible food (FAO and 'The State of Food and Agriculture, 2019), (Zilia et al., 2021). Furthermore, food waste accounts for almost 50% of the global municipal solid waste emissions (Kaza et al., 2018). With regards to fishing, the increase in its consumption is causing damage to several species, which are now on the brink of extinction (Delgado et al., 2003). Additionally, a considerable amount of waste is represented by the discarded fish: animals that are thrown back (alive or dead) into the sea after being caught during fishing activities (Zilia et al., 2021), (Caruso, 2015). The last available data indicates that the discarded fish was equal

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to 8.57 million tonnes in 2018. In other words, this means that we are throwing around 10% of the fish and marine animals we catch back into the sea or ocean (Ritchie and Roser, 2020). Despite the lack of information and available data that makes it difficult to quantify the actual waste, we should consider the daily discarded fish across the entire supply chain, particularly during transformation processes at the firm and household consumption levels. Indeed, approximately 20 million tonnes of fish products are wasted each year, which is equivalent to a quarter of the world's annual catch (Zilia et al., 2021), (Caruso, 2015), (Kim and Mendis, 2006). This industrial processing of seafood by fisheries results in considerable waste, posing a real and growing problem that has a negative impact on the environment (Ravindran and Jaiswal, 2016). Furthermore, it is believed that some fishing industries are also threatening ecosystems (Zilia et al., 2021), (Arvanitoyannis et al., 2014). Several causes of fish waste include products that are caught and not sold due to their low commercial value (Caruso, 2015), damaged goods, improper supply chain management, and improper storage of the product, as well as waste resulting from domestic consumption (Zilia et al., 2021).

There are also species such as sea urchins, whose waste is abundant due to the high content of inedible parts, namely test, spines, and viscera (Raman and Gopakumar, 2018). In fact, the only edible parts of sea urchins are their gonads, which only make up 10–30% of the entire sea urchin mass (Marzorati et al., 2021). Additionally, the increased demand for sea urchin consumption in recent years has raised serious concerns about sustainability, particularly in areas such as Sardinia in Italy, where sea urchins are at risk of extinction.

Considering that the waste derived from the processing of sea urchins is abundant, it is essential to obtain useful nutrients from them to create new sustainable products. In the specific case of sea urchins, it is possible to extract marine collagen, a complex macroprotein that has approximately 20–30% of all proteins found in living organisms present in nature (Pozzolini, Scarfi, Giovine, Kim). Moreover, other compounds can be obtained from the exoskeleton and spines of the sea urchin, mainly calcium carbonate (Ca), magnesium (Mg) and antioxidants (Coppola et al., 2020)– (Campus et al., 2022). Additionally, recovering nutrients from seafood products is a sustainable approach for managing waste, which can help to reduce it (Ravindran and Jaiswal, 2016). Therefore, the aim of this study is to highlight the potential derived from sea urchin waste, thus implementing a circular economy capable of creating new eco-friendly products.

Specifically, this work focuses on the elements that make up the sea urchin supply chain and on the possible reuses of inedible scraps, with the support of a Life Cycle Assessment (LCA) analysis to understand which prospects are the most promising. The manuscript is structured as follows: Section 2 delves into some aspects of waste management; Section 3 provides a concise overview of the European sea urchin market and trade; Section 4 explores various possibilities for reusing sea urchin waste to create eco-sustainable products or applications. By focusing on the Business Model Canvas Approach, Section 5 examines the key definitions related to business models in the literature and provides an illustration of an integrated sustainable business model based on the environmental aspects of transitioning the sea urchin industry. Additionally, this section assesses the environmental performance of a sea urchin waste valorisation pathway through the use of a Life Cycle Assessment (LCA) approach. More specifically, we considered sea urchin waste as a substitute for calcium carbonate used in egg production from laying hens. Section 6 presents a brief discussion of the main results, while Section 7 concludes the study, highlighting future directions, limitations, and areas for improvement.

2. The problem of waste management

Waste management has seen an evident development in the last 40 years, however, there is still room for improvement (Romero-Hernández and Romero, 2018). Before the beginning of the circular economy approach, waste management followed the traditional linear economy, where consumers buy, use, and then dispose of their products (Hockerts and Weaver, 2002). In general, waste management efforts are limited to the 3Rs principle: reduce, re-use and recycle. However, these attempts do not maximize the potential value of solid waste (Romero-Hernández and Romero, 2018). In contrast, the creation of a circular economy system transforms waste products into revenues streams: it helps to increase revenue by using previously discarded products (Romero-Hernández and Romero, 2018).

In general, waste generation is linked to population, urbanization, and affluence. In many developed and developing countries with increasing population, prosperity, and urbanization, it remains a major challenge for municipalities to collect, recycle, treat, and dispose of increasing quantities of solid waste (Bogner et al., 2007).

It is possible to highlight four main key factors influencing global growth in solid waste: urbanization, competition for natural resources, technological change, and climate change with pollution. Generally, it is reported that urban dwellers produce approximately twice as much waste as rural dwellers. Additionally, more sophisticated, and high-quality products do not always lend themselves to effective waste management, leading to a large accumulation of electronic devices in landfills (Romero-Hernández et al., 2009). Finally, poor management and disposal of solid waste are partly responsible for greenhouse gas (GHG) emissions. Annually, 11.2 billion tonnes of solid waste are generated worldwide (Luttenberger, 2020), contributing up to 5% of global greenhouse gas emissions (UNEP, 2019).

There are several types of solid waste, but municipal solid waste is largely significant. Globally, the ORMSW counts about 2.01 billion tonnes per year (Kaza et al., 2018). However, this value is expected to increase up to 2.2 billion tonnes by 2025 (Luttenberger, 2020). On average, each person generates about 0.74 kg of waste level per day, though this value tends to increase or decrease depending on the socio-economic context of reference (Kaza et al., 2018). In fact, the ORMSW generation also rates from the economic development of a region, the degree of industrialization, the education of citizens and the local climate.

According to several studies, residents in urban areas produce about twice as much waste as those in rural areas (Kaza et al., 2018), (Hoornweg and Bhada-Tata, 2012).

In the last decade, the problem of municipal solid waste is an aspect that is increasingly influencing the legislator's agenda. The need to address this threat led countries to the Paris Agreement on climate change, reached at the end of the 21st Conference of the Parties to the UNFCCC (COP21) in December 2015 (Robbins, 2016). In addition, during the UN Sustainable Development Summit in September 2015, all the United Nations Member States adopted a system based on 17 Sustainable Development Goals (SDGs), known as UN Agenda 30, to achieve in the near future. Six of these SDGs are related to solid waste management: Quality Education (SDG 4) in the sense of awareness and related to circular economy and sustainability, Decent work and economic growth (SDG 8), Industry, innovation and infrastructure (SDG 9), Sustainable cities and communities (SDG 11), Responsible consumption and production (SDG 12) and Partnership for the goals (SDG 17). In addition, several governments have implemented policies and regulations to force national companies to improve their waste management strategies. However, this transition is difficult to complete. To minimize solid waste production, there are some solutions that can be adopted as the framework shows. The best known and most used method for waste management is based on an inverted pyramid scheme (Fig. 1). At the top are the best solutions to manage waste, while not even getting close to the bottom (represented by the top upside down) there are the less favourable practices, such as the disposal of waste in landfills and/or incinerators (Papargyropoulou et al., 2014). In the middle there are other steps that refer to the 3Rs principle.

Fig. 1. Traditional hierarchy of waste management. Source: authors' elaboration based on Papargyropoulou et al., 2014.

3. The global' sea urchin harvest and trade

Although the sea urchin harvest represents a niche market, it has always been of great attraction to academics and economists due to its high commercial value. The Fishery and Aquaculture Statistical Time Series software (FishStatJ FAO) provides some relevant information on production, trade, and consumption of marine species; however, the dataset does not consider all edible species of sea urchin. The available species for research are black sea urchin, Chilean sea urchin, European edible sea urchin, purple pacific sea urchin, sea urchins nei, and *strongylocentrotus droebachiensis* (FAO and Aquaculture Statistics, 2022a). Furthermore, the database does not exclude other animals from the echinoderm phylum, such as starfish, sea cucumbers, brittle stars, or crinoids. Additionally, due to the lack of information, the historical datasets appear to be updated only up to 2020. Consequently, the data about sea urchin production discussed in this paper should be considered a rough estimate, but still useful in understanding the dynamics of the market for this product.

Providing a general overview of the global sea urchin' production, it should be underlined that most of the harvest - specifically the gonads of both sexes called roe - occurs in the temperate regions of the world (Zilia et al., 2021).

As shown in the stacked histogram (Fig. 2), from 2000 to 2020 the trend of global sea urchin production slightly decreases until it stabilizes at a more modest value. Indeed, in 2020, the latest year of available data, the total production of sea urchins harvested amounts to 71,186 tonnes, compared with the 93,122 tonnes of the beginning of the XX Century (FAO and Aquaculture Statistics, 2022a). Moreover, Chile is the dominant producer of sea urchin with a value equal to 37,464 in 2020 (FAO and Aquaculture Statistics, 2022a).

Latin America represents an important fishing area, suitable for sea urchin harvest. In fact, Peru and Mexico, alongside Chile, contribute more than half of the world's harvest of this product (FAO and Aquaculture Statistics, 2022a).

3.1. The sea urchin market in emerging countries

As mentioned above, Chile is the main producer of the sea urchin market. It is divided into 12 regions, but the suitable harvesting area is limited to X-XII regions in the south of the country (Andrew et al., 2002).

In the northern Chilean regions, the sea urchin fishery is managed by means of an artisanal fishing system, called the *caleta system.* It consists of a small-scale co-management of the local fisherman's harvest (James et al., 2016). On the one hand, this helps safeguarding the traditional fishing of the poorest villages of the Chilean coasts, and, on the other hand, using the fisherman's contribution in the sea urchin catch at national level (Moreno et al., 2006). In contrast, in the southernmost regions, the fishing has often been poorly managed and invasive, despite the attempts of the central authorities to regulate and discipline it (e.g. a national register of the fishermen, a rule to forbid the fishing during the spawning season and the adoption of a norm that established the size of the minimum catch (MLS) allowed to be at least equal to 100 mm (Andrew et al., 2002).

Another emerging country that plays a key role in term of sea urchin harvest is Russia. Indeed, *Strongylocentrotus intermedius* is harvested along the eastern coasts and most of it is exported to processing plants in Japan, mainly located in the Hokkaido region (Andrew et al., 2002). However, not only Russia is considered as the largest supplier of live sea urchins of Japan, but also one of the world's leading suppliers of frozen sea urchins (Stefansson et al., 2017). In 2020, Russia caught 8041 tonnes, while Japan was slightly lower with 6800 tonnes (Fig. 2) (FAO

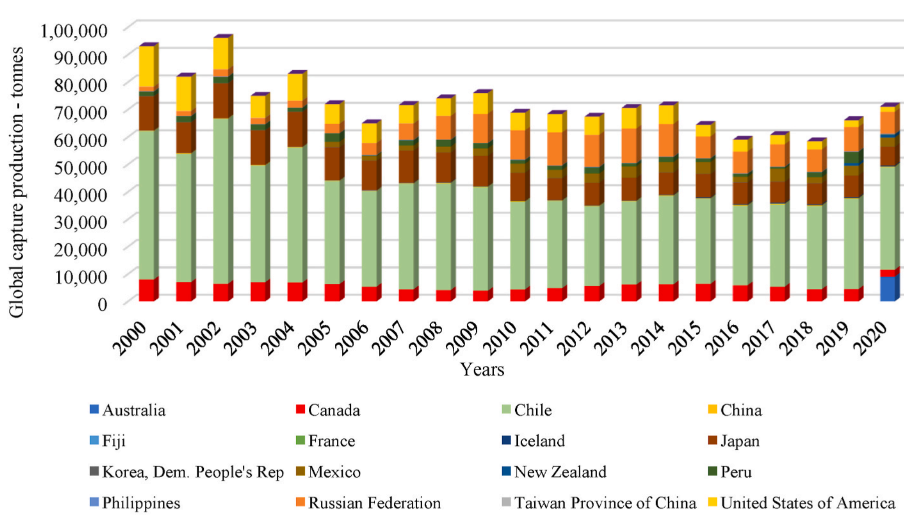

Fig. 2. Global capture production of sea urchin: quantity in tonnes value between 2000 and 2020. The most relevant countries in terms of sea urchins harvested. Source: authors' elaboration based on FAO FishStatJ database, 2022.

and Aquaculture Statistics, 2022a). However, it should be noted that these data are underestimated due to illegal sea urchin harvesting practices and the lack of regulation in the country, which make accurate counting of annual production highly complex (Stefansson et al., 2017).

Russia is one of the main countries in the world that are increasing their sea urchin fishing activity. However, the need make this product more accessible might be an opportunity to introduce in the market less known species and of lower quality to reduce the average selling price (Stefansson et al., 2017).

3.2. Other relevant markets

In 2020, the United States of America and Canada, respectively harvested 1872 tonnes and 2496 tonnes (Fig. 2) (FAO and Aquaculture Statistics, 2022a). Although in recent years both countries have followed a decreasing trend, coherent with the global sea urchin's production, both Canada and the USA represent a world resource in the supply of this product. Specifically, in the West Coast of Canada important processing function of the local fresh roe are carried out, and then exported to Asia, mainly to China, Japan, Hong Kong, and Taiwan (Stefansson et al., 2017). Besides being an important trading partner of Asian countries, Canada also supplies the neighbouring United States, with about 460 tonnes per year of live sea urchins, and this is possible thanks to the specific trade agreements between the two countries and the geographic proximity (Sun and Chiang, 2015).

In the United States, the sea urchins' harvest regards several States, both on the Atlantic and Pacific Coasts. In the States of Oregon, Washington, and California, the most caught species is *Strongylocentrotus franciscanus* - widely exported to Asia – while *Strongylocentrotus droebachiensis* (also known as the green sea urchin) is characteristic of the State of Maine. After being locally harvested and processed, the green sea urchin is usually delivered to New York, where it is either domestically sold or exported to Japan (Sun and Chiang, 2015).

While in Europe, the sea urchin market can be divided into two categories according to the species of sea urchin harvested and traded. Northern European countries generally catch *Strongylocentrotus droebachiensis*, while Mediterranean countries *Paracentrotus lividus*. These two categories followed a different historical process. Fishing for sea urchins in the South of the continent only emerged in 1990, due to a past of poor management and inadequate fishing controls (James et al., 2016), while in the North, the harvest of *Strongylocentrotus droebachiensis* is not exploited by all countries, in some cases consider sea urchins as harmful environmental parasites for the ecosystems of algae forests (James et al., 2016).

The main European supplier of sea urchins is France following by Italy and Iceland. The main European markets, located in the capitals, act as hubs for mainly the HORECA channels, while a small part of the production is intended for supply fishmongers (Stefansson et al., 2017). Even though the retail sales of sea urchin are minimal, it is usual to find some pasteurized sea urchin roes in supermarkets, especially during the Christmas period (Stefansson et al., 2017).

3.3. Sea urchin aquaculture

In recent years, the harvesting of sea urchins has attracted widespread public interest as these species may be at risk of extinction in the future. Among the major problems, we highlight illegal fishing, bycatch and damage to the seabed caused by the use of dredges, and the increase in sea temperatures.

As regards to the phenomenon of illegal fishing, it takes place to circumvent several regional and national regulations, which allow the harvest of sea urchins of specific size and only during precise periods of the year. Furthermore, as in the case of the Sardinia region, in Italy, regulations have been approved over the years which provide for the catch of sea urchins for a specific daily quantity and for a certain number of authorized companies. In addition, depending on the sea urchin harvesting areas and the species, the authorities regularly implement sea urchin harvesting shutdowns for several months of the year. Measures like these are used both to deal with the phenomenon of illegal activities and to safeguard sea urchins by protecting them during the reproduction period.

In recent years, various studies have emerged which associate the production of sea urchins with aquaculture (Rubilar and Cardozo, 2021)– (Dvoretsky and Dvoretsky, 2020). According to FAO data, global capture production of sea urchins in aquaculture was estimated to be just over 9000 tonnes in 2020 (FAO and Aquaculture Statistics, 2022b). The markets that make the most use of this farming technique are Asian, such as China and Japan. The latter is the main consumer of sea urchins, accounting for 90% of the entire world demand. Moreover, thanks to its culinary tradition and its association with sushi cuisine in bars, restaurants and catering, the sea urchin is highly appreciated by Asian populations (Sun and Chiang, 2015). For these reasons, to meet the growing domestic demand, ponds are being developed for the breeding of sea urchins in Asian seas. In addition, there are numerous projects that are focusing on the breeding of sea urchins in aquaculture. According to some studies, it would be possible to reproduce sea urchins in tanks containing filtered wastewater from super-intensive fish farms, together with seaweed such as *Ulva* (commonly known as sea lettuce), useful as nourishment for the sea urchins themselves (Shpigel et al., 2018).

Although the production of sea urchins in aquaculture is only for a niche market, in the near future this practice could offer significant opportunities for different activities that require large quantities of fish products and a constant supply (Capoccioni, 2017). Furthermore, another advantage of aquaculture is the stability of prices on the market, in fact, organic fish products are not subject to price shocks like other similar non-farmed fish products (Capoccioni, 2017). Finally, the breeding of sea urchins in aquaculture together with a circular economy approach could also generate benefits in the fight against illegal fishing activities or harvesting techniques harmful to species and ecosystems.

4. Reuse of *Paracentrotus lividus* waste for environmentally friendly applications

Although the majority of fish processing waste is disposed of in landfills, nowadays this management is detrimental both from an economic and environmental point of view.

It is interesting to underline that these wastes, in several cases, contain significant amounts of nutrients for plants and soil, that can be employed as fertilizers for the cultivated land. This appears to be a sustainable alternative to landfill disposal (MacLeod et al., 2006)– (Lee et al., 2010). Although there are still few studies in this regard, new or potentially elaborated products deriving from the waste generated by the sea urchin, can be an added (Mamelona et al., 2010).

Among several possible applications, waste deriving from *Paracentrotus lividus* (henceforth commonly called sea urchin) can contribute in many ways to the improvement of the soils, thanks to its chemical and biological properties (Garau et al., 2012). The new sub-acid soil, worked with sea urchin waste, rich in phosphorus, active carbonate, and high pH, facilitates the development of beans of the *P. vulgaris* species (Garau et al., 2012). Although this first research is still in the fact-finding and experimental phase, it has shown how to create a sustainable waste management of sea urchin scraps for environmental purposes. In addition to the several research carried out on sea urchins and their physio-chemical properties for the reuse of waste, there are others related to the application of marine collagen obtained from the sea urchin.

Collagen is a complex of macro protein that has about 20–30% of all proteins found in living organisms present in nature (Ferrario et al., 2017), and it represents the main structural component of the extracellular matrix in connective tissues, such as skin, cartilage, and ligaments and in the interstitial tissues of the parenchymal organs (Coppola et al., 2020).

On an industrial level, collagen is mainly extracted mainly from calf skin and bones, a practice that involves serious risks linked to the transmission of infectious diseases (Di Benedetto et al., 2014). Moreover, because of the risks that this practice entails, the use of this type of collagen was limited first by the EC regulation n. 999/2001 and later by the EU regulation n. 142/2011 (Coppola et al., 2020). To find new sources of safe collagen extraction, experiments and research have been conducted. The collagen obtained from marine organisms like sea urchins, was tested, and not only did it turned out to be easier to obtain, but also safer than the one resulting from traditional practices (Di Benedetto et al., 2014). Furthermore, marine collagen is not subject to restrictions and the extraction obtained from the scraps of fish, crustaceans and sea urchins does not interfere with the different religions and with the culture of some populations in worshiping animals considered sacred (Coppola et al., 2020). Therefore, thanks to its properties, the collagen can be used as a support in various sectors as an aid to biomedical devices, dermal implants, cosmetics, and food (Zilia et al., 2021). In particular, several working groups with which the authors of this study collaborate, aim at the complete reuse of waste from the sea urchin food industry to reconvert them, according to a logic of circular economy, into high value-added products. By exploiting the characteristics of the sea urchin's tissues, the goal is to use part of the waste to extract collagen and to design customized medical devices (a sort of "substitute" for the skin) to facilitate wound healing (Marzorati et al., 2021), (Barbaglio et al., 2012). The remaining part - the "shell" called test - is instead used to produce a flour rich in calcium and antioxidants, as an addition to the feed for laying hens. Moreover, the biocarbon portion will be exploited as an enrichment component in the production of feed for the aquaculture of sea urchins, and also of other marine species of commercial interest. This is a clear example of circular economy that seeks to use waste to obtain new products or applications that do not require the exploitation of new virgin raw materials, thus contributing to the reduction of environmental impact.

5. Setting up a circular and sustainable business model for sea urchin

Over the past few decades, since the late 19th and early 20th centuries, the success of a business has been clearly demonstrated in terms of financial gains to the shareholders through dividends and appreciation of a company's worth (Handy, 2002). This focus on financial advantages, rather than the integration of social, economic, and environmental factors, has contributed to a variety of common social, financial, and ecological problems. The concept of a modern business model emerged during the late 1990s, due to the growth of the Internet, which proposed to challenge existing financial models, for example by providing "free" services to their user base (Amit and Zott, 2001), (Boons and Lüdeke-Freund, 2013).

Zott and Amit (2010) depict a business model network according to a standpoint of ongoing activities. This shows the growing belief that business models must be built from a network-oriented perspective rather than a single firm-oriented perspective.

One of the most remarkable as well as illustrious tools employed is the Business Model Canvas (BMC), which interprets a firms' business rationale, as it indicates the principle of how a firm generates, delivers, and bags value (Osterwalder and Pigneur, 2010), (Osterwalder, 2004). Due to the model's adaptability, the BMC has become a universal reference for business model innovation as well as an area of research. In fact, it is acknowledged in every successive publication. The Canvas contributes means to interpret, devise, and enforce a new business model or evidently spruce up the old model (Joyce and Paquin, 2016). It is used throughout the world by all kinds of firms be it small or large size. It is represented by a schematic paradigm including a number of perspectives and it defines the relations between four business ideas: organization's value proposition, framework, customers, and revenues (Brousseau and Penard, 2006).

The BMC structure is comprised of nine essential building blocks which explain the rationale behind a firms' strategy to gain monetary value (Osterwalder and Pigneur, 2010). The blocks are categorized into two major sections. Value distribution is dealt with on the right side of the value proposition and on the left side is dealt with value creation (Chesbrough and Rosenbloom, 2002). Although the BMC is a widely used visual architecture for planning a business model, it hides some limits to its application (Zilia et al., 2021). From an economic and strategic point of view, the BMC mainly highlights the internal links to the company, omitting external factors such as competition and market forces (Coes, 2014). Furthermore, the BMC focuses on maximizing profits, partially hiding the environmental and social value of a specific business (Joyce and Paquin, 2016).

In recent years, the concept of sustainable business model has been developed. The aim is to give companies the opportunity to change their economic system and help them achieve more sustainable goals (Rashid et al., 2013), (Stubbs and Cocklin, 2008). Furthermore, sustainable business models are seen as a source of competitive advantage (Porter and Kramer, 2011). Sustainable business models can be defined as business models that include proactive management of multiple stakeholders, financial and non-financial value creation, and a broad range of long-term stakeholders (Geissdoerfer et al., 2018), (Bocken et al., 2016). According to Stubbs and Cocklin (2008) a sustainable business model is defined as *"a model where sustainability concepts shape the driving force of the firm and its decision making so that the dominant neoclassical model of the firm is transformed, rather than supplemented, by social and environmental priorities"*. Therefore, in our study we feel the need to integrate the model with additional tools and methodologies that can make the business model canvas more dynamic and specific for the case study of the reuse of sea urchin waste. To meet this need, the Triple-Layered Business Model Canvas (TLBMC) is used *"to* support *the creative exploration of sustainable business models and innovations oriented towards sustainability more generally"* (Joyce and Paquin, 2016). In other words, the TLBMC is a valuable aid for companies to better plan the production of innovative products according to an economy model attentive to social and environmental impact. These three layers conceived by Joyce and Paquin (2016) specifically create different values, e.g., economic, social, and environmental. This approach provides a more comprehensive and holistic view that supports more sustainable development. Furthermore, the TLBMC can also integrate with a circular economy system (Lahti et al., 2018), thus offering many advantages for the company that adopts it. Indeed, it can limit its costs by reducing waste, by renewing its production with materials that would generally be discarded and by establishing a better relationship with customers (Lahti et al., 2018).

For our purpose, we will only analyse the environmental layer focusing on the environmental benefits deriving from the reuse of sea urchin waste and the ways in which the product life cycle occurs (García-Muiña et al., 2020). Therefore, using a Life Cycle Assessment our goal is to estimate the environmental impact of collagen and eggs by laying hens produced using sea urchin waste. All this, using the most applied environmental indicators, such as carbon and water footprint, acidification, etc. Moreover, considering this model it is possible to identify negative and positive externalities on the environment generated by the company's activities.

5.1. Life Cycle Assessment of calcium carbonate substitution by sea urchin waste

About 70% of the waste arising from the sea urchin utilisation is represented by the exoskeleton (Marzorati et al., 2021). The exoskeleton is composed of multiple calcium carbonate plates and can be used as substitute of the calcium carbonate supplemented to the feed of laying hens. In this case, the valorisation of seaurchin waste in the egg production chain involve a double benefit. From one side avoid the consumption of calcium carbonate while from the other side offset the impact related to the waste management. The environmental performances of calcium carbonate substitution with sea urchin exoskeleton were evaluate using the LCA approach. LCA is a well-recognized and widely accepted tools for the evaluation of the potential environmental impacts related to processes, services and products. Defined by two ISO standards (ISO, 14,040 and 14,044) (Arvanitoyannis et al., 2014), (Arvanitoyannis, 2008), (ISO 14044, 2006), the LCA is based on the inputs and outputs analysis of the evaluated systems and allows the quantification of different environmental impacts (called impact categories). In this study, the LCA was applied considering the management of 1 kg of sea urchin waste as functional unit and with a “gate to gate” system boundary. The Recipe LCIA method (Huijbregts et al., 2017) was applied to characterize the following environmental impact categories: Global warming, Stratospheric ozone depletion, Ozone formation, Human health, Fine particulate matter formation, Ozone formation, Terrestrial ecosystems, Terrestrial acidification, Freshwater eutrophication, Marine eutrophication, Mineral resource scarcity, Fossil resource scarcity.

Two scenarios were evaluated:

- Baseline (BS), where the sea urchin waste was not valorised, and it is managed as ORMSW (organic fraction of municipal solid waste). Consequently, the waste is partially composted (45%) and partially treated in anaerobic digestion plants (35%) or in landfill (20%) (Saer et al., 2013), (Kibler et al., 2018).
- Alternative (AS), where calcium carbonated is replaced by the sea urchin exoskeleton. In this case, the sea urchin waste is processed (drying, sifting and grinding) and then supplemented to the laying hens feed instead of calcium carbonate. Regarding the drying, a two-step process was modelled considering natural drying and drying in a dried fuelled with natural gas. In detail, considering the experimental trials carried out, the reduction of the water content from 40% (initial moisture content, evaluated during lab scale measurements) to 30% was carried out by natural drying while from 30% to 8% was achieved using a dryer. Besides this, a 10% loss and a 1:1 ratio of substitution between sea urchin exoskeleton (screened and ground) and calcium carbonate were taken into account. The lost waste is managed as in BS. Fig. 3 reports the system boundary considered in the two scenarios.

Table 1 reports the absolute environmental impact for the two scenarios while the relative comparison is shown in Fig. 4. For all the evaluated impact categories, the alternative scenario shows better environmental results respect to the Baseline one. This is mainly due to the substitution of calcium carbonate and, secondarily, to the avoiding of traditional organic waste management. In details, for 8 environmental impact categories this scenario results in an environmental benefit because the sum between the environmental benefits due to the avoided

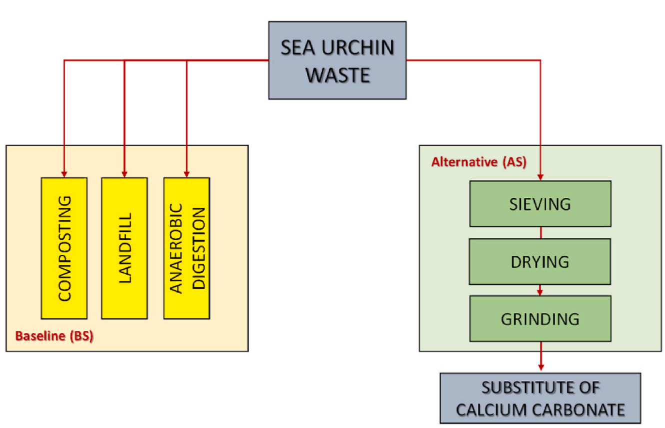

Fig. 3. The system boundary for sea urchin waste with the two scenarios considered.

Table 1
Absolute environmental impact results for the management of 1 kg of sea urchin waste in the two evaluated scenarios: Baseline – BS and Alternative – AS.

Impact category	Unit	BS	AS
Global warming	kg CO_2 eq	0.224	−0.207
Stratospheric ozone depletion	mg CFC11 eq	0.088	−0.089
Ozone formation, Human health	g NOx eq	0.012	−0.916
Fine particulate matter formation	g PM2.5 eq	−0.028	−0.393
Ozone formation, Terrestrial ecosystems	g NOx eq	0.011	−0.937
Terrestrial acidification	g SO2 eq	−0.224	−0.953
Freshwater eutrophication	g P eq	0.984	0.037
Marine eutrophication	g N eq	0.070	0.004
Mineral resource scarcity	g Cu eq	−0.046	−4.914
Fossil resource scarcity	g oil eq	−0.740	−79.588

calcium carbonate production and to the substitution of conventional waste management is higher than the one related to the processing of sea urchin wasta valorisation.

The role of calcium carbonate substitution can be appreciated also in the Fig. 5 where the results for the contribution analysis for AS are shown. The contribution analysis (Fig. 5) highlights how, among the different operations required for the valorisation of the sea urchin waste the drying is the more impacting. In this regard, a possible impact reduction could arise from the optimization of natural drying and to the use of renewable energy for the drying process.

6. Results and discussion

The pressing issues of climate change, rising greenhouse gas emissions, and growing solid waste accumulation call for swift and responsible action from policymakers and all citizens to reverse these negative trends. This study draws attention to the potential for waste to give rise to new eco-sustainable products. Although the sea urchin market is a niche one, the possibilities arising from its waste are numerous. Our focus in this work has been on reusing the exoskeleton waste of sea urchins to obtain a powder that can be used as a feed supplement for laying hens, replacing calcium carbonate. A Life Cycle Assessment (LCA) showed that the Alternative scenario of reusing these waste results in benefits compared to the Baseline scenario of waste being considered ORMSW. However, these preliminary results must be confirmed in future LCA studies that consider the entire life cycle of egg production and consider any potential impacts on the welfare of laying hens and variations in the taste or nutritional value of the eggs produced.

This work also wanted to integrate LCA with the environmental framework of the Triple-Layered Business Model Canvas conceived by Joyce and Paquin (2016).

The core of the Environmental Layer is represented by the Functional Value (Fig. 6). It defines the primary yields of a firms’ activities, which offers a thorough explanation of the product’s performance, or the demands met by the product system. As a result, the Functional Value is the sum of the products utilized by the consumers over a specific time (Zilia et al., 2021), (Joyce and Paquin, 2016).

In the case study, the Functional Value is represented by the sale of sacks of feed for laying hens, weighing 25 Kg each with the powder deriving from the sea urchins’ exoskeleton. In the Life Cycle Assessment, the Functional Value corresponds to the Functional Unit, where the latter indicates the amount of product that is used as a reference for the computations of the flows of materials and energy used in the system both inbound and outbound (Arvanitoyannis, 2008). In this case the Functional Value is given by 1 kg of sea urchin waste to evaluate the two scenarios BS and AS.

A limit represented by the environmental canvas is that given by the distribution channels. If on the one hand the reuse of sea urchin waste to obtain eco-sustainable products represents an eco-friendly business model, on the other hand the distribution channel is based on the traditional methods of road transport, with consequent related problems

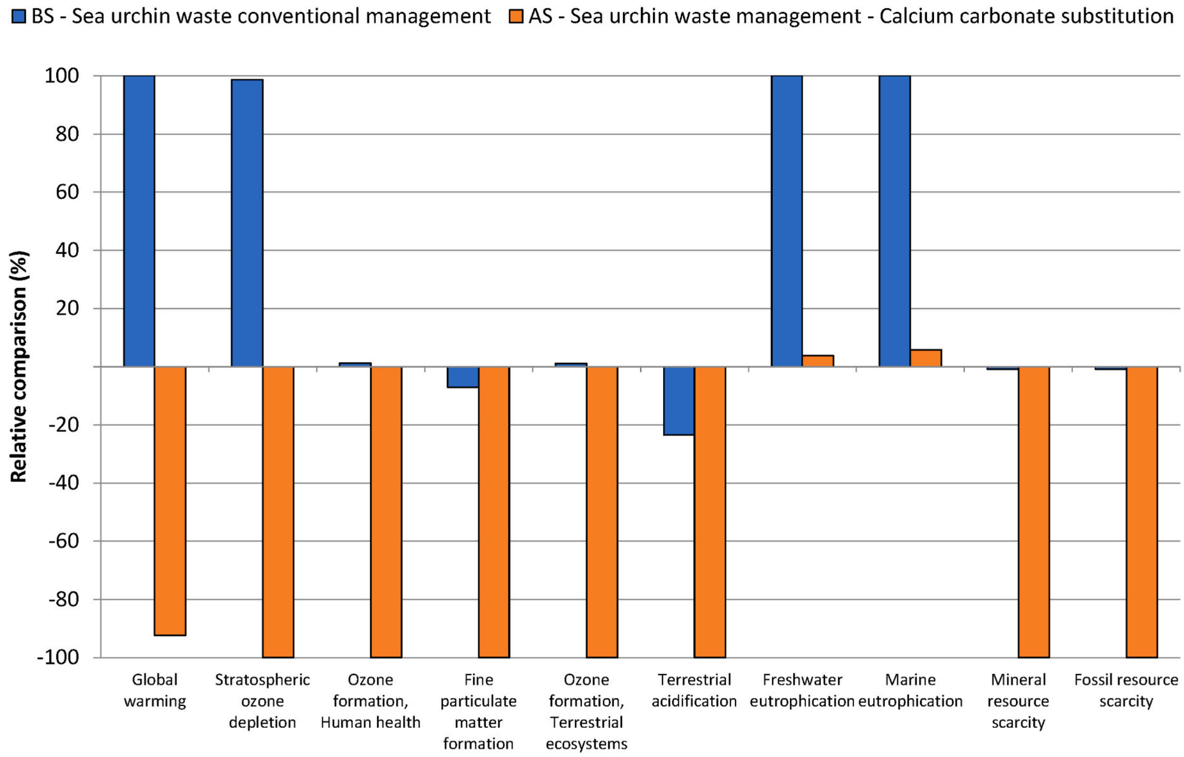

Fig. 4. Relative comparison between the two scenarios.

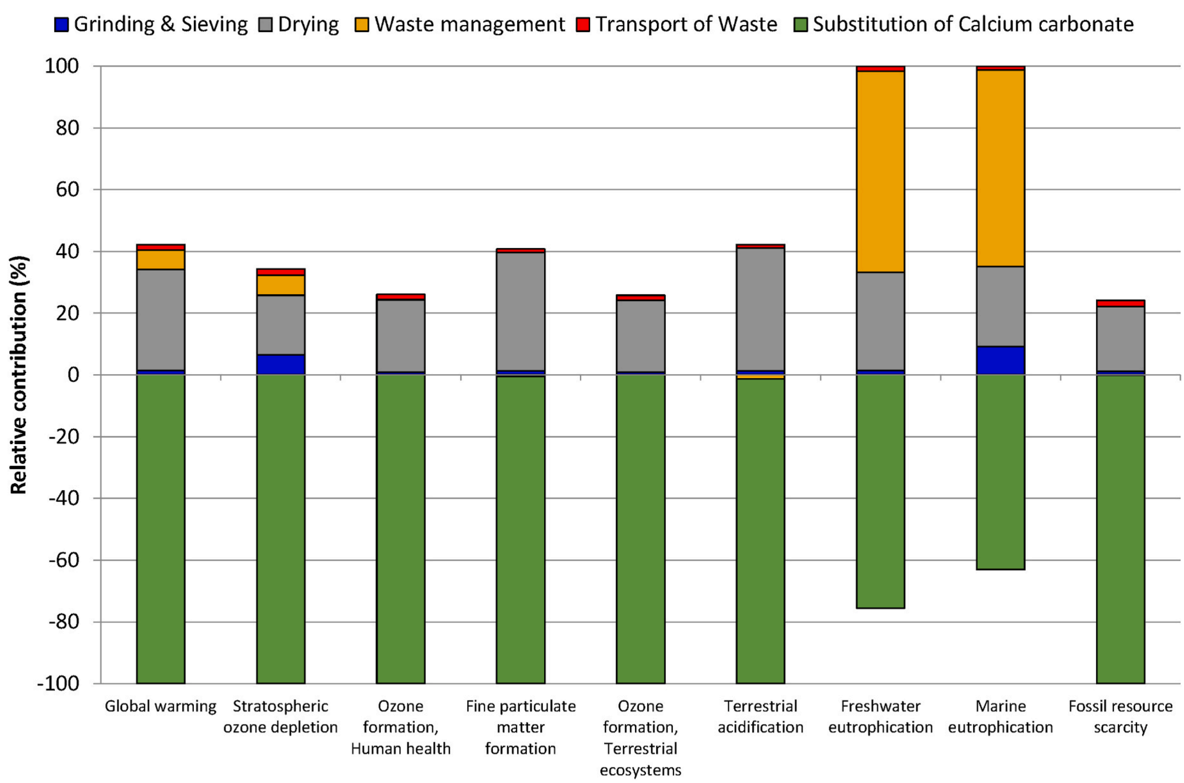

Fig. 5. Results of the contribution analysis for the Alternative scenario (AS).

likes pollution, traffic, and CO_2 emissions. Furthermore, another important aspect of the Environmental Layer is the use of materials to package the product in question. Materials are physical and biological shares employed to create Functional Value (Joyce and Paquin, 2016). In the case study it is conceivable to imagine animal feed packages with eco-sustainable and fully recyclable packaging in the End-of-Use phase of the product (Fig. 6). In addition, the environmental benefits section considers the company's commitment to reduce the environmental impact of production, for example, by providing the product with a positive ecological value (Joyce and Paquin, 2016). In general,

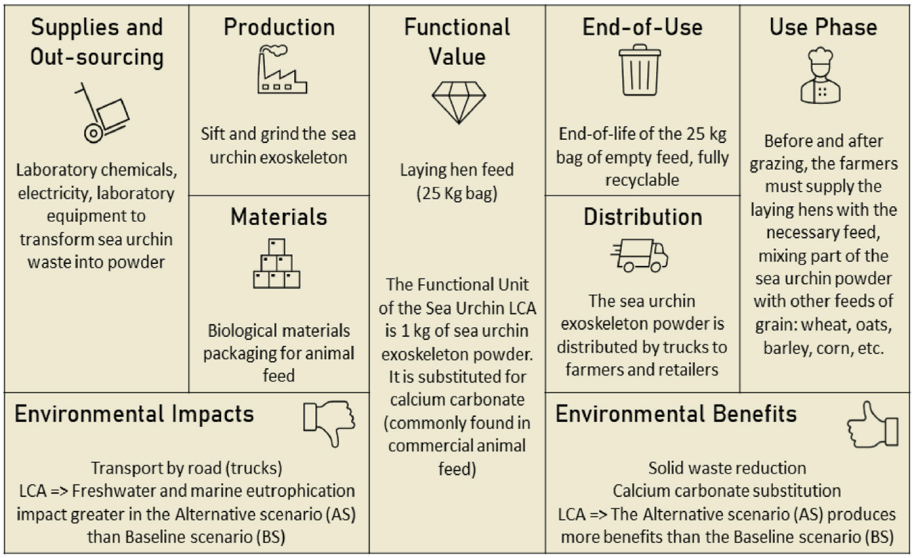

Fig. 6. Environmental Layer of the Triple-Layered Business Model Canvas for the reuse of sea urchin waste. Case study of sea urchins' powder as a feed supplement for laying hens. Source: authors' elaboration based on Joyce and Paquin, 2016.

companies should pursue three main objectives of the green economy: the use of resources in an eco-efficient manner to reduce waste and energy consumption, product innovation to minimize the loss of biodiversity, and the reuse of discarded products (Zilia et al., 2021), (Geissdoerfer et al., 2017). In this regard, companies that process sea urchins can reuse the waste either to extract marine collagen or to create a powder suitable for feeding laying hens. These practises partly reduce the problem of ORMSW. In fact, in Section 5.1., the Alternative scenario of the LCA shows more environmental benefits than the Baseline scenario based on disposal. In addition, the Alternative scenario of the LCA includes the recovery of several elements, such as calcium carbonate, magnesium, and antioxidants from the sea urchin exoskeleton. Moreover, the transition from a linear economic system to a circular approach can help generate social benefits. If companies that process sea urchins are able to implement a strategy based on the reuse of waste, in the near future they will contribute to the economic development not only of their own business, but also that of the local community – for example, by creating new jobs (Padilla-Rivera et al., 2020). Employees may have the opportunity to attend training courses to acquire specific skills (Wijkman and Skånberg, 2017), such as understanding collagen extraction techniques or recovering calcium carbonate from the sea urchin test. Finally, through research projects conducted in conjunction with sustainable activities based on the reuse of waste obtained from sea urchins, it is possible to raise community awareness of more general environmental problems, such as illegal fishing, by-catch, or damage caused by invasive fishing techniques.

7. Conclusions

Although climate change, greenhouse gas emissions and other environmental damage are ever-more pressing issues, many businesses are still reluctant to adopt more sustainable models. However, it is becoming increasingly clear that consumers prefer sustainable products (Mazzocchi et al., 2022), in order to counter the constantly rising production and consumption of raw materials, which can lead to negative externalities such as an accumulation of waste. This new economic system shifts the focus from producing new products to reusing, repairing, renewing, and recycling discarded items. Hence, this model moves from considering waste as a new useful resource.

Eco-innovations combined with developed business models such as sharing, rental and repair, will be able to guarantee companies the creation of new products and markets, thus offering many business opportunities for these firms. In addition, companies should consider the environmental and social layers deriving from their activities, planning a Triple Layered Business Model Canvas, to better focus their core business. Among the several opportunities that the market offers, that of the sea urchin certainly turns out to be interesting and full of potential to be seized in the near future. The study also highlighted how sea urchin waste can be reused for new innovations in the fields of biomedicine, pharmaceuticals, and cosmetics. In addition, thanks to the antioxidant properties deriving from the exoskeleton of the sea urchin, once dried and grinded, it is possible to obtain a powder useful as animals feed that require high doses of carbonate. The powder is characterized in its mineral and pigments content. In fact, the pigments contained in *Paracentrotus lividus*, the sea urchin species under investigation, are of high interest.

The Life Cycle Assessment analysis conducted in the case study highlighted how the Alternative scenario (AS) represented by the reuse of sea urchin waste significantly reduces the negative impacts compared to the Baseline scenario (BS) of the disposal of organic fraction of municipal solid waste. The only two categories where the environmental impact is lower in the BS are those of Freshwater and Marine eutrophication. Therefore, the LCA study of sea urchin waste integrated with a sustainable business model has highlighted how it is possible to create new eco-sustainable products of high value with benefits for the environment. However, given the width of the topic, it is necessary to consider other relevant aspects, such as e.g., massive fishing, processing seafood products waste and illegal fishing. Among the possible solutions, a better cooperation between producers could be very beneficial in preventing overproduction (i.e., when the supply on the market exceeds the demand). In this case, the excessive production of one company could offset a shortage of another company's harvest, thus avoiding the need to exploit additional resources which would then risk remaining unsold and discarded. Another achievable option is to increase market surveys on consumer preferences in supermarkets.

Indeed, consumers are more likely to buy new diversified products, as long as the quality is high and not modified in taste. Moreover, the market research tool can be a valuable support for companies to better understand and direct their production on consumer demand and preferences basis, so as to minimize waste or the accumulation of unsold goods. In addition, governments, especially those in developing countries, should invest more in infrastructure and transport, giving companies incentives to further develop storage and cold chain facilities, the latter essential for the conservation of products such as fish.

Furthermore, it is necessary to improve public awareness, which can be achieved through better education in schools, with the support of political actions that target the community. This can help to foster a new mentality, one that is aimed at reusing what is commonly considered "waste". Through this manuscript, we have sought to promote research on how to convert waste into useful products. This approach could be beneficial in reducing the negative externalities associated with the fishing sector, both for humans and the environment, and in implementing a model of circular economy.

The present work sheds light on certain limitations in the study of the sea urchin supply chain. Firstly, the complexity of reconstructing the supply chain is compounded by the lack of data concerning the species harvested and the quantities of products discarded. As a result, it is challenging to provide exact numbers, and it is only possible to offer truthful estimates. This limitation is partially due to the problem of illegal fishing, which is a significant issue in the fishing sector, especially in the harvest of high-value commercial products such as sea urchins. Another limitation of the study pertains to the distribution channels of a potential product derived from sea urchin waste. At present, it is challenging to envision a logistics system that deviates from the traditional one based on transport via road, ship, or air. On the one hand, reusing waste could result in a reduction of solid waste, but on the other hand, the distribution of the product throughout the supply chain, and especially from production to sale, would occur through the most common methods currently in use. However, the purpose of this work, which is still in its developmental stages, is not to provide a singular solution to the problem but to consider new sustainable business models that can generate profit for companies while also giving due consideration to environmental and social aspects.

In the future, we aim to investigate the financial aspect of this study by attempting to economically quantify the pros and cons of the traditional and circular economic systems in a business plan. It should be noted that the analysis of eggs produced by hens fed a mix of sea urchin powder is still in the experimental phase, and there appear to be no discernible differences or characteristics compared to the eggs currently available on the market. As such, we will also conduct a consumer analysis to understand their willingness to pay for products indirectly derived from sea urchin waste.

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Author contributions

Conceptualization, F.Z., and L.O.; methodology, F.Z.; software, F.Z., and M.C.; writing-original draft preparation, F.Z.; writing-review and editing, F.Z., L.O., M.C., D.E.A.T., M.S. All authors have read and agreed to the published version of the manuscript.

Declaration of competing interest

The authors declare no conflict of interest.

Data availability

Data will be made available on request.

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