A Triple-Helix Intervention Approach to Direct the Marble Industry towards Sustainable Business in Mexico

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Abstract: The marble industry in Mexico, similarly to the international market, is going through some problems which are characterized by low productivity performance, inconsistency in management and administrative organization, high raw material waste, and negative social and environmental impact. The methodology used in this paper is based on a systematic review of the strategies and solutions used to address these problems reported between 2014 and 2021, including the results of the application of in situ surveys to three marble companies in the Mixteca Poblana region. These surveys are collected in this article alongside industry experience to propose, in a structured way, a three-pronged management approach with the aim of directing the marble industry towards a sustainable industry model. The structure of this approach, based on forms of capital and sustainability dimensions, engages governments, companies, schools and society to guide this industrial sector to become a sustainable business, integrating knowledge and experience of the marble industry processes. We recommend adding performance metrics to this approach to assess the value chain of the marble industry.

Keywords: sustainability; marble; capital forms; production

1. Introduction

Internationally speaking, the exploitation, extraction, and transformation of marble is a model of profitable economic development which has seen exponential demand since the 1980s. However, this industry has reported low productivity levels, high raw material waste levels, and a negative environmental impact generated by its dimension stone extraction and transformation processes [1,2]. In the last decade [3], an assessment of the environmental, social, and cultural factors from a perspective of sustainability within this industry has been provided. The results show the formation of pollutants being discharged into bodies of water, the emission of dust from the cutting processes, the presence of occupational hazards, the creation of environmental noise, and damage to health in Palestine. Similar circumstances have been reported in the marble industry in Turkey [4], where remedial actions have been proposed in order to reduce the damage to workers' health and the environment, and strengthen economic aspects in the marble industry, resulting in a 7% improvement in the productive efficiency of the marble process. In this context [2], to assess the problems of air, soil, and water pollution resulting from stone and marble activities in China, a methodology was proposed that lays the foundations to create a clean production scheme.

In Mexico, the problems in the industry are characterized by low productive performance, a lack of management and organization structures [5], high amounts of raw material waste [6], and negative social and environmental impacts in the two representative marble exploitation areas in Mexico: the Comarca Lagunera and the Mixteca Poblana [7,8]. In this industrial context, actions towards sustainability must be part of the corporate strategy of the industrial sector, with the objectives of raising the quality of life, reducing and eradicating poverty, and minimizing the environmental impact created by this industry [9]. The publication *Governance of Mineral Resources in the 21st Century: Guiding the Extractive Industry towards a Sustainable Development at the 2020 International Resources Panel* has offered suggestions to improve the economic state of the mining industry, alongside encouraging companies to comply with social and environmental standards in order to generate trust among the population and avoid social conflicts. In this context, the 2030 Agenda for Sustainable Development promotes action plans to eradicate poverty, protect the environment, and reduce problems related to climate change. Within the 17 objectives set out in the 2030 Agenda, objective 9—"Industry, Innovation, and Infrastructures"—refers to generating and applying actions to ensure that industry is more productive while significantly reducing carbon dioxide emissions and the amount of waste generated in its processes.

This research is based on the method of the Business Council (BS) for Sustainable Development (2002), and the framework is a diagnostic study of the context and the challenges of the Mexican marble industry in these dimensions: social, political, economic, cultural, environmental, research, and development. Thus, this article contributes a comprehensive management approach of three helices for the integration of forms of capital reported in the Mining, Minerals, and Sustainable Development (MMSD) project of 2006, and the Multidimensional Model proposed by [10], to synergize government, business, school, and society strengths, with the aim of transforming the marble industry sector in the following principles of sustainability. The integration of the strengths of the marble industry in the international arena under a comprehensive management approach of three helices—government–business–school—allows the experiences and knowledge related to the marble industry processes reported internationally to be aligned with the local experience where this comprehensive three-helix management (THM) approach is replicated. With this purpose in mind, the objectives of this article are the following:

- Synthesize the internationally written research articles about the marble industry from 2014 to 2021 and accumulate knowledge to help address problems in this mining sector;
- Suggest the government–business–school approach as a useful intervention guide for researchers to address problems in the marble industry value chain.

In the following sections, we summarize the experience reported by international writings related to problem-solving strategies in environmental, economic, social, cultural, political, and social dimensions, and integrate them into the comprehensive three-helix intervention, or triple-helix intervention (THI), approach for the sustainable development of the marble industry.

2. Materials and Methods

This exploratory and descriptive research integrates the socio-economic and environmental dynamics of the marble industry, reported in the scientific writings from 2014 to 2021, with the objective of relating the dimensional elements of a sustainable company reported by [10] and described in Figure 1, with the forms of capital of the Mining, Minerals and Sustainable Development (MMSD) project reported in the United Nations through ECLAC, i.e., natural capital, manufactured capital, human capital, social capital, and financial capital. As shown in Figure 2, this research uses secondary information sources organized according to [11] which provides a model for the revision of the articles and written research defined by stages of evaluation. This model is relevant to describe the technological, productive and environmental context of the Mexican marble industry, supported with international articles. In this research, the primary information was collected

in situ from three marble companies in Tepexi de Rodríguez-Puebla in Mexico by applying five hedonic-level Likert scale surveys validating aspects related to the processes of marble extraction and processing, and which have been reported by international and national research articles.
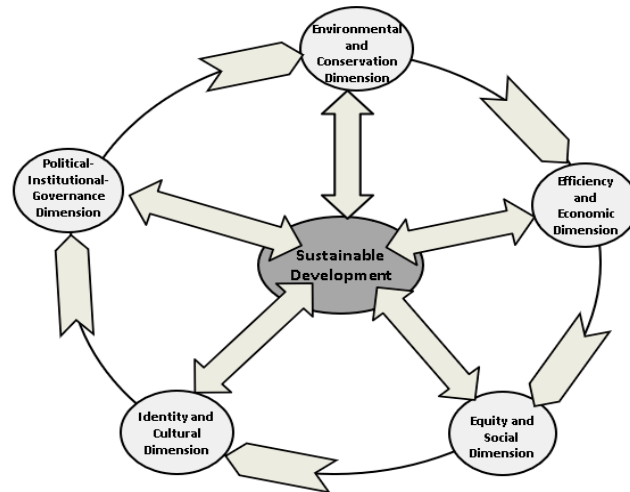
Figure 1. Multidimensional approach (MA) for sustainable development.
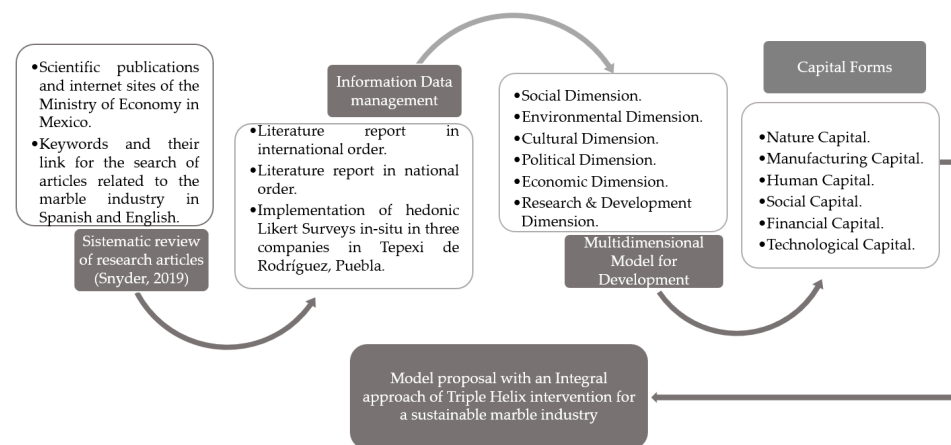
Figure 2. Model proposal with an integral approach and its influence field in the forms of capital for the marble industry in Mexico.

Findings identified in the literature framework and from the in situ research are used in this study for a THI approach to manage the processes of the marble industry towards becoming a sustainable enterprise in relation to economic, social, and environmental progress. The scientific literature has reported the evolution of models with a quadruple- or quintuple-helix approach, in which knowledge of society is highlighted to create synergies between economy, society, and democracy [12]; however, this industry in Mexico is in the process of development. Therefore, it is considered that the mining sector, and specifically the marble industry, in the process of this development, must be oriented so that products' exploitation, production, and transformation are sustainable in order "to" preserve those resources that are essential for human subsistence.

3. Results

3.1. Socioeconomic and Environmental Contexts of the National Marble Industry and Its International Contrast

One of the industrial activities with a great negative impact to ecosystems is the mining industry and, specifically, the extraction and transformation of stone materials, such as

marble. Worldwide, the countries with the largest deposits are Italy, Spain, Portugal, Turkey, and Greece. From these countries, the three main producers are Turkey, with 39%, followed by Italy with 16%, and Greece with 7% [13]. In this industry, Palestine, Turkey, and Pakistan have identified problems inlcuding the unsustainable management of waste resulting from the extraction, transformation, transportation and distribution of marble [14], as well as the demand for large amounts of water for the cutting and polishing processes of the marble cuts, with an estimated annual average of 38,700,000 m^3 [15]. According to [16], the high demand for this resource negatively impacts the communities in which this industry operates due to the discharge of contaminated water characterized by a high content of 95% calcium carbonate, with the remaining 5% comprising chemicals such as calcium sulfide, chrome, zinc, and iron used in the marble cutting and finishing processes [16,17]. This section is divided by subheadings. It should provide a concise and precise description of the experimental results and their interpretation, as well as the experimental conclusions that can be drawn.

On the other hand, the low professionalization of workers in this industry is also a concern, as are the poor conditions in the ventilation and lighting of the facilities, compromising the medium- and long-term health of the workers in this industry [4]. In this context, the absence of good practices in the management and exploitation of quarries, the absence of formally established environmental controls, companies with changing structures and organizations, negative externalities to public health, and push production systems are all factors that affect the integration of the supply chain in the marble industry, and can be divided into economic, social, and environmental dimensions. In this regard [1], it is highlighted that the lack of strategic association with suppliers and customers, the lack of communication and integration between areas, as well as the absence of marketing plans and inventory management, consequently impact the disarticulation of processes which, in turn, greatly affect the profitability of the company, and increase negative externalities. Recently [3], it was reported that, in Palestine, the marble and stone industry has negative effects on public health, the environment, water resources, and ecosystems, as well as causing noise pollution and radical changes to the environment landscape where this industry is located.

In Mexico, the marble industry has been growing in economic activity since the 1960s, with two areas dedicated to exploitation and extraction of marble: Comarca Lagunera, with 15 municipalities [18], and the state of Puebla with 5 municipalities [19]. The statistical yearbook of 2019 Mexican Mining reported a production of 1,964,041.14 tons, with an estimated value of 12 billion dollars [20], which shows that this type of industry meets a demand that strengthens the economy of the country. However, the negative externalities caused by its exploitation, transformation, storage, and distribution must be considered [21]. A disarticulation between economic agents and, consequently, a push type of production is reported, which generates the excessive waste of natural and human resources, negatively impacting economic, social, cultural, and environmental factors. Meanwhile, [8] it has been emphasized that the marble industry has collaterally created large amounts of waste from its extraction to finishing processes, without having a responsible final disposal for them, with the waste being thrown into open-air landfills.

The Ministry of Economy of Mexico in 2020 reported that, in the extraction and exploitation stage, there have been performance problems in terms of the efficient use of resources, low levels of safety, and the effective use of the minerals, as well as low economic profitability, due to the fact that artisanal and improvised techniques, as well as the use of machinery in poor technological conditions, continue to be used. Hence, ref. [6] it has also been identified that small companies in this industrial sector are technologically backwards.

The recommendations identified through the research performed on this sector place special emphasis on the fact that the marble industry requires an in-depth analysis and an action plan to remedy its negative externalities and to lead this sector towards being a sustainable industry. Figure 3 shows that the marble industry in Mexico had a rise in 2014 and a significant drop in production in the following years.
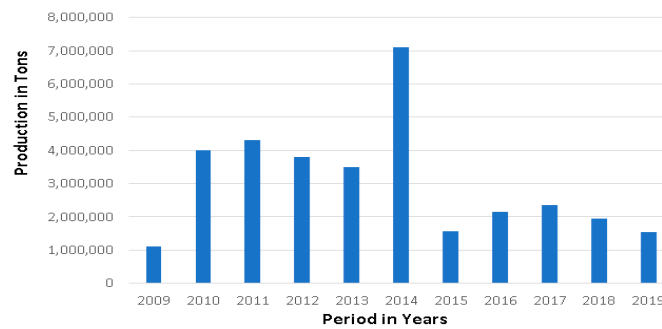
Figure 3. Marble production volume in Mexico from 2009 to 2019.

Various authors agree that the problems faced by the Mexican marble industry can be summarized by social, political, cultural, and environmental dimensions. The Ministry of Economy of Mexico have emphasized the importance of giving this industry an impulse from the start point of exploitation of the stone so that problems hindering its progress can be addressed. To achieve this, experts in the sector, as well as Mexican mining organizations and the Mexican Ministry of Economy, highlight the importance of learning from the experiences of other countries such as Pakistan, Turkey, Iran, and Italy which, despite encountering the same problems as Mexico, have shown some signs of progress in the productive and environmental dynamics of the marble industry.

Table 1 illustrates the challenges the marble industry faces in Mexico that require the attention of the scientific community and stakeholders in this industrial sector. The common problems in the two marble industrial zones in Mexico are summarized by negative externalities to public health and damages to the green mantle, soil, and air; inefficient processes from excessive exploitation of the rocks in the quarry; and waste in the extraction of the dimension rocks and in the lamination process.

Table 1. Problems and challenges of the marble industry in Mexico.

Dimension	Problem	Challenge
Social	The marble industry in Mexico is characterized by the participation of the community and agricultural actors who have this marble industry as their primary source of income. This industry's operation has negative effects on public health caused by dust, environmental noise, and occupational hazards [22]. Technical advice is not available for this industry; there are no financing programs with the scope of the productive investment required by this sector [5,23].	- Manage and promote effective links with research centers that provide advice to guide and exploit the marble industry in a sustainable manner; - Within a three-helix framework (THF), manage advisory programs for the exploitation of marble reserves; - Identify those public policies that promote and bring together marble entrepreneurs and the *ejido* communities to address the social problems arising from the activities of the marble industry to find suggestions and solutions; - Implement occupational hygiene and safety management systems that guarantee the physical health of the workers who provide their services in the quarries, and marble processing companies.
Political and Economic	The productive and technological situation faces problems characterized by inefficient processes, poor organization and administration, added to technological obsolescence and conventional methods still being applied. The previous mentioned aspects impact the low use of the dimensional marble stone, and more quality defects also start showing [8]. On the other hand, as a non-concessionable activity, the extraction of marble is exempt from the payment of mining rights at a federal level. Hence, there has been an increase in excessive exploitation without considering a geological analysis of the mine and land where these deposits are located.	- Establish public policies that regulate the exploitation of marble deposits; - Identify programs that promote the marble industry in its different stages of the value chain; - Encourage school–company relationships for the development of competitive advantages in the marble industrial sector.

Table 1. *Cont.*

Dimension	Problem	Challenge
Cultural	Various externalities of the marble industry that transcend in the community´s cultural changes, for example, working in marble factories and leaving lands to cultivate [24]. For this reason, populations living near the areas of marble exploitation and extraction demand that their rights, customs and traditions are not altered by the marble mining activities. There are also reports of water scarcity in the municipalities where this industry is located [17].	• Develop strategic alliances between interested parties and organizations that participate directly and indirectly in the marble industry (*ejidatarios*, business owners, entities at local, state, and national government levels); as well as private organizations, higher education universities and research centers to create collaboration networks for mutual government–society–business benefit.
Environmental	The marble industry in Mexico has an impact on green mantles [7] and the irregular consumption of water resources [17], as well as affecting local landscaping [5]. These problems are attributed to the extraction, cutting and transformation processes of dimension stones.	• Promote practices and processes, under a socially responsible culture, to regulate environmental policies so that the marble industry can be led towards sustainable development; • Identify three-helix association mechanisms aimed to manage and promote circular economy models based on marble industry waste; • Identify linking mechanisms between public and private organizations to establish strategies for the treatment of discharges to soil, air, and water that come from polishing, smoothing, and special processes; • Develop collaborative strategies between public and private organizations and the marble industry to carry out environmental impact evaluations before and during industry operations, as well as in quarry operations.

3.2. International Marble Industry: Problems and Solutions

Table 2 shows that one of the problems of great concern in the marble industry in the international context is waste management; secondly, the low quality in the finishing process and the productivity related to the efficient use of raw and in-process materials are also concerning. On the other hand, as shown in Figure 4, in this industrial sector, job security is a large problem, yet it receives little attention in the industry: most of the proposals for improvement are frequently focused on reducing waste generated by this industry. Likewise, the least managed issues are those oriented to environmental safety, and the treatment of industrial effluents from this industry. Those problems raise the possibility of waste management and the treatment of its effluents from a circular economy approach. The proposed solutions show that they are focused, with greater importance, on addressing the problems related to occupational health and safety, as well as negative externalities caused by dust and environmental noise [4]. The waste generated by the marble industry—essentially pieces of laminated marble and sludge from marble cutting—have caused obvious environmental damage that range from changing the landscape [6] to impact on flora and fauna, in addition to the pollution caused by the emission of marble dust into the air, causing respiratory diseases [25]. Given the fact that these events have been reported in international articles [2], the authors recommend carrying out environmental performance evaluations and looking for alternative economies that are useful and marketable [4].

The reality faced by the marble mining sector in the international order, and its contrast in the national order, show similar scenarios. In Mexico and other parts of the world, the low efficient use of marble in its extraction and transformation processes [6], the damage to the health of workers and of local people in the community in this industry [25], and the high amounts of waste and sludge created [3] are among the most recurrent problems. To that effect, given the scenario of declining production shown by the industry in Mexico (Figure 3), several authors recommend improving the processes of marble extraction, transformation, and distribution.

Table 2. Problems and solutions of the marble industry in some countries.

Author	Country	**Problems**						**Solutions**					
		Supply Flow	Water	Safety	Health	Waste Management and Handling	Quality and Productivity	Logistics and Productive Strategies	Recycling and Water Treatment	Safety and Hygiene Programs	Professionalization of Collaborators	Circular Economy Strategies for Waste	Environmental Performance Evaluation
[14]	Palestine	X	X	X	X		X	X	X		X		X
[26]	Cuba	X				X		X				X	
[27]	Turkey		X	X					X				
[16]	Pakistan		X	X					X				X
[4]	Turkey	X					X	X			X	X	X
[8]	Spain						X	X					
[28]	Peru					X						X	
[29]	Spain					X						X	
[1]	Ethiopia	X					X	X			X		
[30]	Spain					X						X	X
[31]	Egypt					X							
[2]	China					X							X
[32]	Pakistan		X						X			X	
[33]	Guatemala						X	X					
[34]	Spain					X						X	
[35]	India					X						X	
[36]	Egypt					X						X	
[3]	Palestine		X	X	X		X			X	X	X	
[37]	Turkey						X	X					
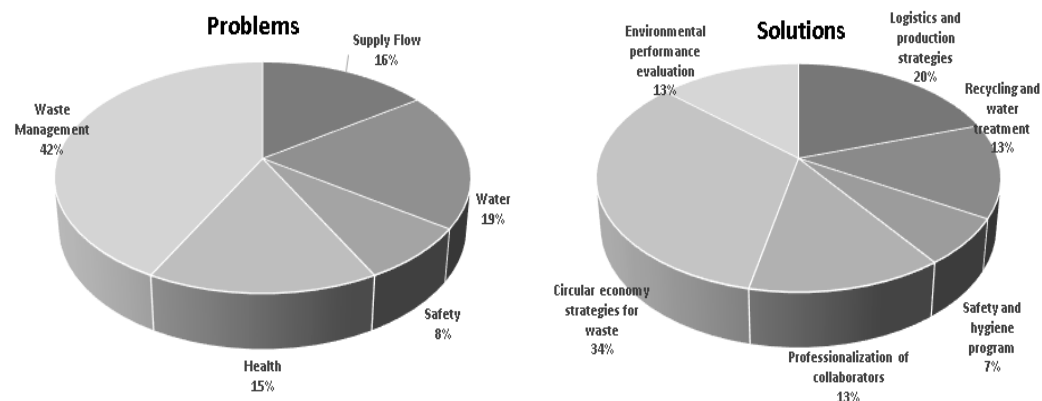
Figure 4. Proportion of the problems and solutions of the marble industry internationally.

4. Discussion

Conceptual Approach of Triple-Helix Intervention for the Marble Industry in Mexico

The dynamics of emerging economies motivate industries to innovate to increase competitiveness and promote the economic development of the region where they are embedded [38]. Currently, academics and researchers observe the convergence of the activities

of citizens, companies, the government, universities, and society with great attention and interest. This idea describes the conceptual approach of the quadruple- and quintuple-helix models. However, in the current context of the marble industry, especially in emerging countries such as Mexico, social intervention behaves only as a regulatory body of industrial practice. To that effect, we propose initiating the transition towards the sustainability of this industry through a conceptual model of THI: government–company–school. In this regard, the findings reported by international research on the problems of the marble industry and the fieldwork of three marble companies located in Tepexi de Rodríguez in Puebla, Mexico, coincide with the importance of the intervention of the government, companies, and universities to manage an efficient and friendly marble industry in a socially responsible environment. It is evident that the problems and challenges of the marble industry in Mexico are not unrelated to those presented by industries in other countries. Some experiences in the different dimensions of sustainability have been internationally covered in different articles. These experiences have made it possible to address specific problems when public policies, research, and responsible societies are presented.

The Ministry of Economy and the Ministry of Mining recognize that Mexico has an important diversity of marble reserves that have not yet been quantified, and that its quality allows it to compete internationally. Therefore, it is important for direct and indirect agents to participate in this industry, and to tackle the global environmental regulatory challenges to transition towards a sustainable industry. Countries in the European community are already on this path towards a sustainable marble industry.

In the 1990s, the United Nations—through the division of natural resources and infrastructure—carried out a reform of the mining laws in Latin-American and Caribbean countries. These agreements essentially focused on the economic aspects and, later, relevance was given to the environmental dimension [9]. However, the social dimension was not addressed, causing the mining industry to reflect an imbalance affecting sustainable development. The report *Governance of Mineral Resources in the 21st century: Gearing the Extractive Industry towards Sustainable Development at the 2020 International Resources Panel* identified suggestions to improve the economic performance of the mining industry to ensure compliance with social and environmental standards. Moreover, this report observed a series of guidelines so that this sector could establish a governance structure that addresses safety and resource efficiency. These approaches motivated replacing the concept of "Social License" with "Sustainable Development license" and "Operate". The first built trust among the population and avoided social conflicts, whereas the second works under an integrating approach, with the objective for companies to achieve positive environmental, social, and economic results with fairer agreements, taking part in positive actions for the environment and stakeholders so that local customs and traditions can be preserved.

In this train of thought, it is necessary to create "alternatives for life and the general welfare without compromising the ability of future generations to meet their own needs" [39], which is the case of the mining industry and, especially, of the marble industry. In this respect, the report of the project MMSD (2006) describes that, to satisfy the needs of current contexts without affecting future generations, things must be sorted in an effective way [40]; in other words, the available capitals must be produced and exploited in a reasonable manner, considering the preservation of those fundamental for human life. The MMSD project (2006) defines five forms of capital as a valuable investment for the sustainable operation of the mining sector: natural, manufactural, human, social, and financial.

Natural capital provides a sustained income from ecosystem benefits, such as biological diversity, mineral resources, clean air, and water. Manufacturing capital transforms natural capital to create consumption value, and is defined by machines, facilities, and infrastructure. Social capital is represented by groups and institutions that make collaborations between people and groups possible. Financial capital is the representation and result of the natural, manufacturing, human, and social capitals [40].

Figure 5 concentrates this set of elements in terms of dimensions and forms of capital with which [10] positive impacts will contribute to improve production practices along with environmental quality, resulting in a positive impact on the community by addressing common interests from a multidimensional systematic perspective with the collaboration of specialists and social actors. This intervention approach seeks to integrate synergies based on partnerships between stakeholders so that the marble industry can transition to sustainability. The author of [9] notes that collaboration agreements and the creation of communication channels are two necessary aspects in a world with an empathetic and responsible society. This work scenario is strengthened by [23], which recommends creating committees as managers to monitor the operation of this industry. With this purpose in mind, the design and permanent assessment of the performance of the different operations from the supply of dimension stone and throughout the chain of economic actors of this industry is necessary.
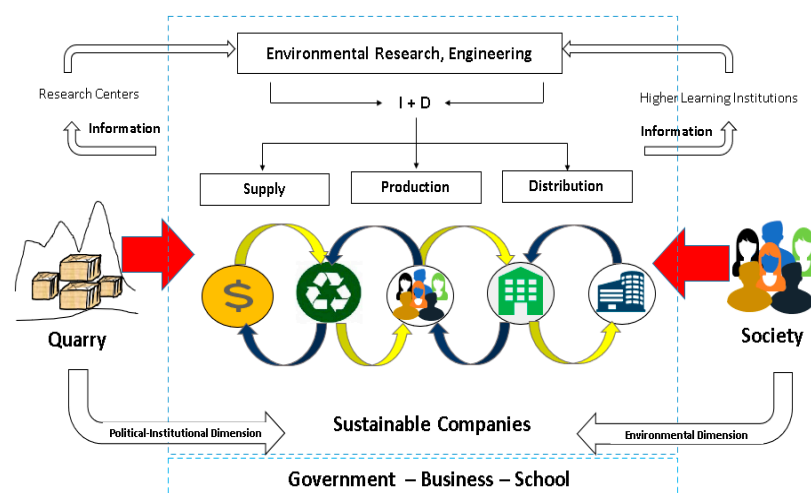
Figure 5. Comprehensive THI approach for sustainable development in the marble industry.

In essence, the sum of the efforts of all intervening actors, directly and indirectly, is fundamental for the development of this national industry. Hence, many research centers and universities have created connections or partnerships in regard to research and development (R&D).

This school–company relationship can be seen, for example, in India [35], where they have created a recycling alternative for approximately 12 million tons of marble waste under the concept of a sustainable circular economy approach. In Turkey, the successful transformation of marble and the costs involved were documented by the computational program of the mathematical model of linear programming of mixed integers, which solved the problem of marble cutting waste and the planning of marble cutting [37].

In Ethiopia [1], a research project was carried out to determine the factors that affect the performance of the supply chain of the marble industry, supported by a review of information from research documents, the application of surveys, interviews, and descriptive statistical analysis. The results provided recommendations with emphasis on creating a strategic partnership between customers and suppliers through an electronic communication network for the management of operations in the extraction and transformation of marble. In Peru, similarly to the case in India, a study that reused marble waste for the construction industry, reported by [28], demonstrated the usefulness of these residues to manufacture concrete with a resistance of 279.18 kg/cm^2 through mechanical resistance and comprehension tests, showing greater resistance compared to the formula of conventional concrete.

In regard to health, safety, and the environment in Turkey, problems related to human factors (noise and lighting) and to the environment (reuse of waste, water, sludge) were solved by using the Inventive Problem-Solving Theory (TRIZ), which resulted in an increase

in productivity of more than 7.5%. The author of [5] documented the characterization of the marble production chain in the state of Puebla so areas of opportunity could be identified regarding raw material, transformation processes, and organizational knowledge. From this research, a series of recommendations, such as those reported in Ethiopia by [1], could be emphasized, leading to the efficient integration of the production chain, the creation of new management and organizational practices, and the diversification of marble products towards new national and international selling markets.

These findings highlight the importance of government–business–school conections to undertake improvements throughout the value chain in the marble industry. For this purpose, Figure 5 shows a comprehensive THI approach for the development of the sustainable marble company. This approach, based on a government–company–school relationship as an intervention manager, seeks to bring research centers and universities closer together to carry out research and the innovation of these processes throughout the supply value chain, including supply, production, and distribution. The improvement interventions in the marble industry supply chain are managed as capital reported by the MMSD project (2006), and the dimensions are oriented towards those of a sustainable company, as reported by [10]. In this THI approach, society has an important role in which permanent communication is maintained to assess the impact of the benefits and externalities caused by the marble industry.

Given the dynamics of emerging economies, some studies have argued for the need to apply actions aimed at innovation, entrepreneurship, and economic development through the synergistic work of companies, governments, and universities in a triple-helix management approach [41]. However, given the development observed by academic and research bodies, the need in these economies to incorporate the social sector as a manager oriented towards business innovation stands out [42].

Based on the comprehensive proposal of the triple-helix intervention to guide the marble industry in Mexico towards sustainable development, it is important to establish a descriptive model of the stages where all components, dimensions, and forms of capital converge to create processes that are efficient and friendly to the social and environmental surrounding contexts (Figure 6).
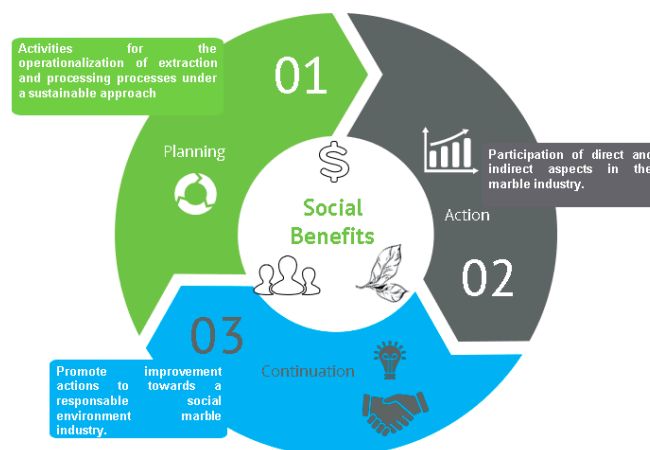
Figure 6. Descriptive functional model of the THI aproach in the marble industry.

Figure 6 shows the three stages of the descriptive functional model. The planning phase, from a systemic approach, allows the comprehension of the context of the productive and environmental dynamics in the marble industry, leading it towards sustainability. In the next section, the action stage, the direct and indirect variables are fundamental so that the transformation, logistics, and service processes can generate social benefits with activities that elicit more efficient and productive dynamics, considering social and ecological implications. Based on the forgoing, the third phase of "continuation" emphasizes the universal measures that help to quantitatively assess the performance of the marble

industry in regard to the labor, production, and environmental aspects, through a permanent evaluation in which indicators will be identified, managed, and referenced to ensure continuous improvement.

5. Conclusions

The exploitation, extraction, and transformation of marble have structured a model of profitable economic development which has observed a significant economic exponential increase since the 1980s. However, this industry in the international market has reported low levels of productivity, high levels of raw material waste, and a negative environmental impact generated by its extraction and transformation processes. In this context, the marble industry in Mexico presents similar problems with its two representative zones: the Comarca Lagunera and the Mixteca Poblana. To solve these problems, the literature reports various strategies. In this article, an approach is presented to intervene in the value chain of the marble industry based on social dimensions and forms of capital, with the aim of integrating the knowledge of public organisations and the experience of stakeholders in this industry to lead it in a sustainable manner. This integrating approach suggests the improvement of the productive processes, including the extraction, transformation, and the distribution of marble. To this end, the integration of the social sector to stimulate synergy between operations should follow the triple-helix model proposed here as a manager of innovation, and leave behind actors with only social claim.

Finally, although the identification of the performance metrics of the value chain have not yet been identified, this approach strives to intervene so that the value chain can be complemented.

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