Research, Society and Development, v. 9, n. 11, e71391110272, 2020
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# State of the art of the development of sustainable concrete for applications in conventional structures

# Estado da arte do desenvolvimento de concretos sustentáveis para aplicações em estruturas convencionais

# Estado del arte del desarrollo sostenible del hormigón para aplicaciones en estructuras convencionales

Received: 11/15/2020 | Reviewed: 11/21/2020 | Accept: 11/26/2020 | Published: 12/02/2020

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**Resumo**

É notadamente perceptível o aumento pela demanda de matérias-primas não renováveis para aplicações nos mais variados segmentos da construção civil, o que de fato proporciona maiores deteriorações ao meio ambiente, seja através dos resíduos gerados na extração, durante o uso e depois do uso. Nesse sentido, este trabalho objetiva realizar uma apresentação do estado da arte correspondente aos concretos desenvolvidos atualmente, enfatizando os de âmbito sustentável que corroborem a proposta ecológica na utilização de resíduos ou rejeitos provenientes de diferentes setores de produção industrial, a fim de dirimirem parcialmente a escória produzida, convertendo-as em matérias-primas para reuso. Torna-se evidente o aumento das propostas de mitigar os impactos ambientais com foco no uso desses rejeitos, o que necessita, dentro da correspondente área de estudo, maiores ampliações das possibilidades de emprego para aperfeiçoamento da técnica de incorporação de resíduos em concretos, com observância na dosagem, no consumo, no fator de empacotamento quando necessário, na densidade dos materiais envolvidos e no aspecto de aplicação do compósito.
**Palavras-chave:** Compósitos de matriz cimentícia; Estruturas convencionais; Resíduos sólidos; Sustentabilidade; Materiais de construção.

**Abstract**

It is noticeable the increase in the demand for non-renewable raw materials for applications in the most varied segments of civil construction, which in fact causes more significant damage to the environment, whether through the waste generated during extraction, during use, or after use. In this sense, this work aims to present the state-of-the-art corresponding to the concretes currently developed, emphasizing those of a sustainable scope that corroborate the ecological proposal in the use of residues and/or tailings from different sectors of industrial production, in order to partially settle the slag produced by converting them into raw materials for reuse. The increase in proposals to mitigate environmental impacts with a focus on using these wastes becomes evident. The corresponding study area requires greater expansion of the employment possibilities for improving the technique of incorporating waste into concrete with due observance of the dosage, consumption, packing factor when necessary, density of materials involved, and application aspect of the composite.

**Keywords:** Cement matrix composites; Conventional structure; Solid waste; Sustainability; Construction materials.

**Resumen**

Se nota el aumento de la demanda de materias primas no renovables para aplicaciones en los más variados segmentos de la construcción civil, lo que de hecho aporta un mayor daño al medio ambiente, ya sea por los residuos generados durante la extracción, durante el uso y después del uso. En este sentido, este trabajo tiene como objetivo hacer una presentación del estado del arte correspondiente a los hormigones actualmente desarrollados, destacando los de alcance sustentable que corroboran la propuesta ecológica en el aprovechamiento de residuos y/o relaves de diferentes sectores de la producción industrial, con el fin de sedimentar parcialmente. la escoria producida, convirtiéndola en materia prima para su reutilización. Se evidencia el incremento de propuestas de mitigación de impactos ambientales con foco en el aprovechamiento de estos residuos, lo que requiere, dentro del área de estudio correspondiente, una mayor ampliación de las posibilidades de empleo para mejorar la técnica de incorporación de residuos al hormigón, con la debida observancia. dosis, consumo, factor de empaque cuando sea necesario, densidad de los materiales involucrados y aspecto de aplicación del compuesto.

**Palabras clave:** Composites matriz de cemento; Estructuras convencionales; Residuos sólidos; Sostenibilidad; Materiales de construcción.

## 1. Introduction

The search for alternative materials for applications in civil engineering has grown considerably in this century, which provides broader aspects of the destination of industrial by-products that previously did not have a correct destination for use in diversified applications: in conventional construction materials or unconventional, contributing as a filling material, in the construction methods, contributing so that in specific stages of a distinct work, the virgin raw material is 100% replaced by a characteristic industrial waste for a given practical case.

Santos, Fontes & Lima (2017) claim that sustainable materials become an alternative that corroborates an important reduction in the environmental impact in the production of construction elements. These are caused by the civil construction sector, which presents alarming rates regarding the use of non-renewable resources, in addition to energy expenditure and the generation of solid waste.

There is a current initiative, well presented by the way, which aims to make it possible to incorporate Construction and Demolition Waste (CDW) into construction materials. Also, industrial waste from the metallurgical, mining, and oil sectors; polymeric and vitreous compositions waste; slag from the granite and marble industry; and by-products from sewage treatment plants start to significantly compose the construction materials matrix, which gradually advances through the improvement of existing studies on each emphasized theme.

Thus, Santos, Fontes & Lima (2017) also highlight that the application of recyclable aggregates, which may come from the CDW, has taken on ever more considerable proportions since there is a current decrease in the natural deposits of large and small aggregates for concretes and mortars. The use of the CDW generated by the demolition of structural concrete parts and other construction elements is also an alternative to replace the aggregates of natural origin in a new composite, either for structural or non-structural purposes. Salles et al. (2020) developed conventional concrete compositions by adding CDW as a substitute for natural aggregate, evaluating the fresh and hardened state's mechanical properties. The authors concluded that recycled CDW aggregate is viable as long as there is also an addition of superplasticizer additives to the compositions. In parallel, the parameters of resistance to compression and flexion were not negatively affected, which confirms the purpose of using the CDW.

In other words, the civil construction industry can absorb its residues and the residues of different industrial sectors. It enables better laboratory results coupled with the partial mitigation of the environmental impacts that they would cause if they were not applied as raw material. This culture of recycling solid waste, created from environmentally sound practices, leverages sustainable development, contributing to the environment by saving non-renewable

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raw materials due to its substitution by industrial by-products. According to Souza, Felipe, Felipe & Lima (2020), "environmental issues related to sustainability make the industrial development goes with sustainable actions linked to its processes."

The creation of composites that have a cementitious matrix that involves sustainable materials, especially recyclable aggregates, started in 1928 according to Paiva (2013), who in his studies aimed to cover the mineral residue from the scheelite processing in conventional concretes, from the same way that Steiner (2011) evaluated the application of porcelain polishing residue to compose the concrete mixture, in addition to Pietrobelli (2010) who studied the addition of polyethylene residue, or pet bottle residue, in concrete mixtures, or even Cabral, Schalch, Dal Molin, Ribeiro & Ravindrarajah (2009) who developed concrete prototypes to study performance from the incorporation of recycled red ceramic aggregates, in the same way as Silveira et al. (2016) who studied the mechanical behavior of concrete with tire rubber, or Betat, Pereira & Verney (2009) that focused on the feasibility of using the residue from the processing of agate for the production of concrete together with the assessment of cement consumption generated by it.

These proposals developed in Brazil are just some of the various possibilities for composing the most used cement matrix product globally, providing sustainable concrete development. Consequently, it holds satisfactory results when the applied materials' physical and chemical properties were analyzed in the same way as the best dosage employed to provide optimizations in each case's manufacturing process. Obtaining sustainable composites leverages a practice beyond optimizing its production chain in exempting the environment from the deterioration caused by the extraction of non-renewable resources. It brings the way of thinking green, getting to the present proposals that can enhance according to the applications requested.

Santos (2008) notes that in civil construction, the last decade was marked by research that aimed to develop new materials that would bring durability together with a possible initial cost-benefit and a relevant mechanical resistance. It aroused measures that proposed the service satisfactory as to the characteristic performance, showing composite materials as technically and economically viable alternatives nowadays through the resources available for such manufacture. According to Ranieri, Martins, Capellato, Melo & Mello (2020, due to the current global concerns regarding environmental problems, parallel to the interest in alternative construction materials, the concept of sustainability has gained greater visibility worldwide, together with rapid technological advances in the construction sector.

Several models are being developed to replace Portland cement-based materials for industrial by-products concerning aggregates and cement. Somehow it gradually mitigates the $CO_2$ emission in the atmosphere due to the large-scale production of this hydraulic binder of great usability in general buildings, mainly when applied in concrete mixtures.

It is observed that Lizarazo Marriaga & Claisse (2009) had this concern with the $CO_2$ emission in the atmosphere due to the high degree of Portland cement manufacturing. Based on Naik (2007), until 2002, they estimated that 2.7 million $m^3$ of concrete were produced worldwide (close to 6.75 billion tons of concrete). In that amount, the use of Portland cement is about 15%, reflecting an immense consumption of this binder as construction (Lizarazo Marriaga & Claisse, 2009).

This 15% consumption links directly to $CO_2$ emissions, equivalent in the 6.75 billion tons of concrete produced to a total of 1.013 billion tons of cement consumed based on the 15% factor adopted by Lizarazo Marriaga & Claisse (2009). According to Ioannou, Reig, Paine & Quillin (2014), a quantity of 930 kg of $CO_2$ is produced for each ton of cement manufactured (±0.95 billion tons of $CO_2$ emitted), considering a specific deterioration in the ozone layer.

Nevertheless, Padilha Júnior, Patriota, Teixeira & Chagas (2015) emphasize that concrete is the most used structural material worldwide. Its low cost and the easy availability of constituent materials makes its use more attractive than other construction materials. As reported by Ioannou, Reig, Paine & Quillin (2014), the estimate that Portland cement's current consumption is close to 3.3 billion tons manufactured globally every year.

Another point of view about cement matrix materials, with an emphasis on concrete, goes beyond destructive and non-destructive laboratory tests to ascertain the mechanical behavior, these being the ones that provide immediate results and projections of the structure's behavior when the first ages of the material. It also includes the durability of the material, which works together with the environment in which it is inserted—the used elements in the composite manufacturing process to influence the composition's final result.

For this, the sustainable components applied in substitution of finite and non-renewable resources need to present characteristics very close to what is required to be used on a large scale. It brings into play the characterization research of these by-products, technically certifying whether the use is viable than those currently used. This conjunctural analysis also occurs through practical application and more intense simulation of environmental conditions, inducing the resistance limit for each tested circumstance of the material under evaluation.

It is clear, according to Cunha Oliveira, Meira, Pessoa, André & Cavalcante (2017), that the increase in the disposal of pollutants generated in the most varied sectors of the industry is intensified as the laboratories analysis technologies advance. In this way, today, it is possible to use residues that have sustainable potential for different compositions and formulations previously not valued.

The objective of this work is to present the state-of-the-art corresponding to the concrete currently developed, emphasizing on those of a sustainable scope that corroborate with the ecological proposal in the use of residues and/or tailings from different sectors of industrial production, in order to partially settle the slag produced, converting them into raw materials for reuse.

## 2. Methodology

As a methodology, a bibliographic search was carried out in the primary scientific databases (ScienceDirect, Google Scholar, and Scielo) about the types of ecological concrete developed in Brazil and the world and ways of applying this unconventional technology. Thus, the ideas advocated at the beginning of this study will be explained according to the types of concretes that have practical application potential, according to each study location, as well as before the respective solid residues that are adopted as renewable inputs in their compositions.

## 3. Theory

The definition of concrete lies on an artificial rock obtained from the mixture of inert materials with different granulometries to the hydraulic binder, highlighting the cement, and the mixing water, producing a liquid of good workability and fluidity that can be molded in different volumetries, reaching high mechanical resistance when in the hardened state after curing and drying in its early ages.

Although composites applications that have cement in their mixture cover a demarcated field in the industrial sector, there are frequently new possibilities to innovate in different ways of composing this material appear every year. Likewise, when the locations of use and the environmental conditions suffer routine changes, the material responds differently to each physical and chemical variable in constant contact, contributing to new studies aiming to support the emergence of undesirable changes in structure pathologies.

The studied sustainable concretes allow, at a given moment, the addition of mineral origin elements- for example, from the burning of by-product or industrial waste, previously discarded in the environment- to be used, which can certainly improve specific mechanical properties in the fluid or hardened state. The concrete can absorb such properties to show permanent effects and bridge the incorporation of harmful microstructure components.

Regarding the scope of these additions, a way for adapting to the sustainable factor is, according to Wilson, Rivera-Torres, Sorelli, Durán-Herrera & Tagnit-Hamou (2017), to produce concretes with low Portland cement content due to the high $CO_2$ emission in the manufacturing process, reaching percentages close to 50% of cement substitution with connecting materials, such as volcanic ash, some diatomaceous earth, tuff or opaline quartz and shale.

Due to the low granulometry of these additives, Isaia, Gastaldini & Moraes (2003) claim that they perform an obstruction of the pores and voids present by the finer grains' action, justified by the physical or filling effect. A more dense and armored material to the attacks of harmful agents is ratified as the final product. The large volume of concrete used is concerning, which causes a vast generation of waste and pollutants linked to high energy consumption and a decrease in the natural reserve of available raw material, which may not meet the growing market demands in the future close to the sector of civil construction, with respect to cementitious matrix products (Ioannou, Reig, Paine & Quillin, 2014).

Since the Portland cement patent registration in 1824, it has been spread worldwide due to its surprising physical properties in the hardened state. It also presents the possibility of being molded in any geometries due to the good rheological properties shown in the fresh state. Mehta (2004) recalls that the concrete construction sector is not sustainable because it consumes excessive amounts of virgin resources. Another reason is that its main component is Portland cement, whose production emits greenhouse gases that contribute to climate change.

Many concrete structures suffer from the requirement of durability, and some production of materials originating from some industrial by-products add to the improvements in terms of durability, such as fly ash (FA). Other products that act following what has been mentioned are active silica, microsilica, ash from burning rice hulls, or volcanic ash, which can produce similar effects in certain samples of Portland cement concrete, including bamboo ash since all these mineral additions have pozzolanic properties according to Silva, Andrade, Rios & Nascimento (2020).

With the evolution of construction methods due to greater standardization, concrete structures have gained more space in the world market. They are widely disseminated through the models of buildings created in Brazil and worldwide. Most of the time, there may be changes in the material, model, or shape, and yet they will receive the same nomenclatures: pillars, beams, and slabs, and their wide use classifies them as conventional structures.

### 3.1 Sustainability

In the face of the most varied research from the perspective of sustainable resources, one of the most studied materials is concrete, converging in the dissemination of innovative proposals and technical-scientific support that suggests improvements in the material's properties when industrial by-products are involved.

Fontes, Toledo Filho & Barbosa (2016) propose using Sewage Sludge Ash (SSA) as mineral addition in materials that have Portland cement. They studied the feasibility of replacing 5% or 10% by weight of cement with SSA in high performance concretes. The criteria applied in the sludge composition are based on the microstructure of the material obtained when compared to conventionally resistant concrete.

Fontes, Toledo Filho & Barbosa (2016) also claim that depending on the case of SSA, having a large presence of heavy metals in its composition (even after the calcination process), a denser microstructure (characteristic of high-performance concrete), makes it more challenging to solubilize these compounds in the environment. Confirming the research's final results, which revealed a mild reduction in compressive strength by 0.6% for the 5% added 365 days old from the specimens.

As for this insertion of SSA in cementitious matrix materials, Chagas (2019) states that this practice minimizes environmental impacts. It also reduces the volume to be disposed of in landfills since this input produced from this by-product generated by most sewage treatment is feasible to use after eventual thermal activation, or even in natura. Thus, Table 1 below presents a brief overview of research that used sewage sludge as a mineral addition to replace Portland cement.

**Table 1** – SSA Research.

| Researcher | Sludge treatment | Incorporation percentage | Conclusions |
|---|---|---|---|
| Tay e Show (1992) | Incineration | 10% a 40% | It is possible to produce cement from sludge, satisfying the normative resistance requirements. |
| Hoppen et al. (2005) | *In natura* (centrifugation process) | 3%, 5%, 7% e 10% | 5% of sludge incorporation can be applied in situations ranging from the manufacture of artifacts, blocks, and concrete pieces. |
| Areias et al. (2017) | Calcination | 0%, 2%, 5%, 10% e 15% | It is possible to indicate a final destination of the ETE sludge as incorporation in red ceramic. |
| Fontes, Toledo Filho e Barbosa (2016) | Calcination | 5% e 10% | The presence of sewage sludge changed the microstructure of the concrete pores, reducing its connectivity. |
| Pérez-Carrión et al. (2014) | Calcination | 10% e 20% | The incorporation of sludge is suitable for the manufacture of precast concrete blocks. |
| Silva, Chinelatto e Chinelatto (2015) | Dehydration at 110°C | 5%, 10%, 15%, 20%, 25% e 50% | Incorporating sludge resulted in high water absorption in the produced blocks, but it is feasible to use ETE sludge incorporating up to 25%. |
| Pan et al. (2003) | Incineration | 20% | Mechanical grinding to adjust the sewage sludge's fineness is efficient to improve the mortars' properties. |

Source: Chagas (2019).

Another application is sugarcane bagasse ash (SBA). According to tests performed by Lima, Sales, Almeida, Moretti & Portella (2011), when a fixed portion of fine aggregate is replaced by SBA in strokes using CP II-E 32 cement, the resistance to compression and surface wear increases significantly when the SBA content encompasses values from 30% to 50%. It contributed to the conclusion that, in general, SBA can be applied in the manufacture of concrete pieces for urban infrastructure in environments of superficial abrasive actions of light intensity.

And as an emblem, the concrete with recycled aggregate (CRA) confirms that within the sustainable sphere that civil construction produces, with results greater than the reference features of conventional concrete with natural aggregates, and for Tenório, Gomes, Rodrigues & Alencar (2012):

> The heterogeneity of the composition; The specific mass with lower density, the acquired quality of the mortar, and the variability of the properties are important characteristics of the recycled aggregates, which represent obstacles not only for its use but also for its reliability in concretes used in structural applications.

In this bias, Tenório, Gomes, Rodrigues & Alencar (2012) studied applying the CDW to concretes, observing the porosity that these recyclable aggregates could add to the mixture and the durability of the material, always compared with a reference feature that would help in a real way in the evaluation of the behavior of the specimens. Based on the tests performed, Tenório, Gomes, Rodrigues & Alencar (2012) checked the applicability of CRAs in structural elements, but with caution in factors such as durability, mechanical, dimensional, and durable properties, which can become limiting when applying CRA in practice.

Rice husk ash (RHA), a non-crystalline silicon dioxide, presents high pozzolanic reactivity and a large specific surface, obtained through the burning of rice husk and significant participation in mixtures with Portland cement application. Its application is for improvements in the durability of concretes and mortars and the mechanical resistance of the material, being the object of study by Givi, Rashid, Aziz & Salleh (2010) being an industrial by-product of cement supplementation with common use. The RHA applied in mortars and concretes, partially replacing cement, is the current study object. It shows considerable importance due to the environmental safety that it provides. Besides adhering to the composites, having greater durability, less hydration heat, less porosity than results in a shield with a greater guarantee against harmful ions that deteriorates the concrete matrix, it also reduces the effect of water capillarity, etc., being effectively a pozzolana that contributes to the properties of the concrete (Givi, Rashid, Aziz & Salleh, 2010).

This pozzolanic reactivity is verified in the oldest structures, which obtained extraordinary durability when the volcanic ash with hydrated lime was thought to dominate the cementing fabric and the material's durability 2000 years ago, with the example of the *portus Cosanus* pier in Orbetello, Italy. Within this view, Jackson et al. (2017) observed that the possibility of structures lasting for centuries is linked to the crystallization process of aluminum tobermorite- a rare mineral, hydrothermal- and with calcium silicate hydrated (C-S-H) in its composition that has cation exchange capacities. The presence of seawater promotes its durability instead of deterioration, a fact that would readily occur in Portland cement-based materials used today.

Moreover, the possibility of applying a combination of FA and RHA in different proportions to concrete, as in the studies carried out by Sathawane, Vairagade & Kene (2013), produced an economical and ecological concrete. When these mineral additives were incorporated in their composition, generating specimens with good resistance to compression, flexion, and rupture at 28 days of age compared to the developed reference feature.

According to the above, there is a relevance in the materials' studies that make up the range of the so-called sustainable in the civil construction' sphere at an international level. Thus, state-of-the-art industrial by-products applied in cementitious matrix materials become more supported and with greater perfection in the results expressed by each study made.

## 4. Discussion

In green thinking, the advancement of the premises that govern the feasibility of using concrete within legalized parameters and ecological composition shapes an important position to develop successful work on the final product. The pertinent literature composes the methodologies that permeate the productive process in the research on the theme. When applicable, the Brazilian norms help provide more specific and more accurate discourse regarding the desired results.

The state-of-the-art that encompasses works of an ecological scope makes it possible for studies developed by Freitas, Violin & Silva (2013); Moura, Leite & Bastos (2013); Rodrigues & Fucale (2014); Lima & Iwakiri (2014); Castellanos, García, Agredo & Gutiérrez (2014); Meira, Ferreira, Jerônimo & Carneiro (2014); Izquierdo & Ramalho (2016); Andrade et al. (2016); Medeiros et al. (2016); Gorninski & Tonet (2016); Portela, Gandia, Araújo, Pereira & Gomes (2020), and so many others, contribute significantly to the increasingly leaner production with less waste, involving in the cement matrix materials organic, polymeric, ceramic, composite and metallic compounds, which demonstrated some particularities when used:

- Organics can behave in various ways when included in the traces of cement-based materials, especially concrete. Due to its particles' size and shape variability, the composite's packing effect in the composite is significant for better refinement of the pores and the porous network's tortuosity. However, in many cases, the residue of organic origin can hold high metal values heavy. It can make it challenging to solubilize them in the environment when the composite produced has a dense microstructure (high performance concretes and/or high initial strengths).
- Polymeric agents contribute significantly to obtain greater resistance to flexural traction, obtaining from 20 MPa to 30 MPa, depending on the type of polymeric residue used in the study, its dosage, its applied format. When subjected to high temperature, it can also increase the resistance due to the post-curing process given the material's initial age.
- Ceramics, in their particularity, bring potentiality with the pozzolanic effect adhered to the material, which sometimes laboratory tests without the palliative of the practical test may prove inadequate in terms of use. However, the applicability is viable because it contributes to reducing the speed of ion deposition chloride.
- Composites, when inorganic, bring good results when used in concretes in general. As they are inert and have characteristics similar to aggregates in their natural form, the porosity they can carry must be carefully observed. When organic, such as wood, the applied residue can cause cracks when used in large quantities (above 50%). However, the adaptation of this residue for use in cementitious matrix products can provide better results.
- Metallics can provide the type of concrete that is made with greater resistance, whether or not the fibers of the waste are ordered, but the type of waste used and the way it is used in the mix can reduce the slump when the Slump Test is performed, which it can induce less use of water to apply additives or additions in order to improve workability.

Thus, it is noticeable that the construction industry permeates a vast space for the development of increasingly exquisite works, which is supported by the benefit that many industrial by-products can bring when used prudently. The produced state-of-the-art corroborates these studies' current productivity. Similarly, it bases new possibilities of increasingly using beneficial resources for both sectors: economy and environment.

## 5. Conclusions

From studying new ways of making something recurrent applicable in practice, it is crucial to think critically: investment in new technologies developed. The difficulty of implementing the latest technique in the market should promote an open discussion that would assist in the development of people's way of thinking, encouraging a demystification that the use of these resources from industrial by-products would hinder the manufacturing process and market attendance in the development of its sales, in the same way that green thinking needs to gain more and more relevance in technology centers since the aspect of sustainable studies is already known. Still, the character of what is created is that it calls into question whether it is feasible or not. Also, measures that are palatable according to the technique studied or improved demand time and involve an economical chain in the industrialized market that could, in the view of businesspeople in large part, not bring benefits to them.

The large-scale use of technologies created, or in most cases perfected, incorporates in the initial stages of planning and creating experimental schedules until the final stages of tests and results tabulate a great possibility of application. However, for these sustainable practices to be used in practice, it is necessary to have the industry as a primary partner, corroborating the effectiveness of what is created within large research centers, inducing the incorporation of these technologies together with what is usually called conventional.

Today's technology supports various ways of studying waste, waste and industrial by-products to compose the sustainable sphere that civil construction so badly needs. In the same way that it allies with the process to considerably reduce the extraction of virgin raw material, mitigating environmental impacts in the long term so that a sustainable culture can emerge in local, regional, national, and global society. This scenario makes it possible to understand that many people seek to highlight the importance of studies on the subject, be in line with environmental laws, and allow more extended materials of finite origin on the planet.

Thus, culturally, the quest to make what is a new part of many people's social routine allows us to highlight academia and industry's actual joint performance. They promote changes in various areas of knowledge. When this performance is strengthened and brings success, the economic and social chains involved share the same success, benefiting the population and especially the place where they live.

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**Percentage of contribution of each author in the manuscript**

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