Production of biomaterials from the recycling of urban organic waste

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Review article

Abstract: Urban organic waste (UOW), a significant part of municipal solid waste, fronts substantial environmental challenges due to its disposal and management. A proper UOW treatment actually needs supplementary ecological issues, and in this context the applicable utilisation of UOW can be inserted to generate new materials.
In this paper, the potential of converting UOW into valuable structural and secondary biomaterials is explored, thereby addressing waste management subjects while contributing to sustainable material production, as well as demonstrating a circular economy approach, emphasizing resource recovery.
In particular, different methods of waste collection, segregation and processing have been examined to optimize the yield and quality of biomaterials for various applications, including biomedical, packaging, biodegradable tableware and sustainable building materials. The research highlights the efficiency of key processes such as anaerobic digestion, composting and thermal treatments - each contributing to different end products with specific purposes - in reducing the carbon footprint and the economic viability of upscaling these recycling initiatives.
UOW can be a promising feedstock for biomaterial production, improving waste management systems and promoting environmental conservation.

Keywords: *urban organic waste; biomaterials; recycling; sustainability; circular economy*

1. Introduction

Inadequate use of food resources intended for human consumption, i.e. food waste including keeping food after its expiry date, leads to food decomposition, bringing detriment to environmental and socioeconomic factors. Reducing consumption, waste and therefore garbage, in general, would therefore alleviate the pressure on limited resources [1]. Opening the food system towards a circular economy helps the environment, improves community sustainability and reduces the impact of global warming, cutting carbon emissions in the atmosphere [2].
Appropriate waste management really requires additional issues by an ecological point of view, and in this context it can be inserted the applicable utilisation of municipal wet waste to generate biomaterials. This production, indeed, is a growing sector aiming to use organic waste from urban areas to create sustainable materials and reduce environmental impact. Municipal wet waste mainly includes food waste and other organic materials. The main key steps involved in the process are:

- waste collection
- separate collection: organic waste is separated from other types of waste at source to facilitate the recycling process
- door-to-door collection or dedicated collection points: citizens are encouraged to dispose of their organic waste in specific containers
- transformation into biomass
- composting: organic waste can be composted to produce nutrient-rich compost, which can be used as a natural fertilizer

- anaerobic digestion: this process breaks down organic matter in the absence of oxygen, producing biogas and a nutrient-rich residue known as digestate [3]
- production of biomaterials
- extraction of compounds: from compost or digestate, it is possible to extract compounds that can be used for the production of biodegradable materials and bioplastics
- biorefineries: can be used to convert organic waste into materials such as bioethanol, organic acids and other useful compounds
- development of bioplastic materials
- polymerization: the extracted compounds can be subjected to polymerization processes to create bioplastic materials
- formulation development: researchers work to develop bioplastic formulations with desired properties for different applications.

2. Utilization of food waste for biomedical applications

This utilization aligns with the principles of the circular bioeconomy, which aims to minimize waste and maximize the value of biological resources. Food waste, which includes by-products and leftovers from the food industry, can be repurposed for various biomedical applications, contributing to sustainability and resource efficiency ([4] and [5]).

The integration of food waste into biomedical applications not only contributes to a circular bioeconomy by reducing waste, but also provides cost-effective and sustainable alternatives to conventional materials in the biomedical field. It's important, however, to consider safety and regulatory aspects when utilizing food waste in biomedical applications, in order to ensure that the final products meet necessary quality standards.

Here are some potential ways in which food waste can be used in biomedical contexts:

- antioxidant compounds
- polyphenols extracted from the waste of fruits and vegetables can be utilized for their antioxidant and potential health-promoting properties, with possible applications in preventing oxidative stress-related diseases; they can be used in various industries, including food and beverages, pharmaceuticals and cosmetics; utilizing waste materials for polyphenol extraction not only reduces the environmental impact but also contributes to the development of sustainable practices in the food industry
- bioactive compounds for disease prevention
- probiotics derived from fermented food waste, which can be incorporated into pharmaceuticals or functional foods to promote gut health and prevent certain diseases: fermented food waste, indeed, contains a diverse range of microorganisms such as bacteria, yeast and fungi, and harnessing these for probiotic purposes can have several potential benefits
- biodegradable materials
- starch and cellulose extracted from plant waste, utilizable to produce biodegradable materials for medical packaging or implants
- biological energy production
- anaerobic digestion of organic waste: food waste can be subjected to anaerobic digestion to produce biogas, which can then be used for energy production or as a heat source in various biomedical processes ([3] and [6])
- biosensors
- enzymes extracted from by-products of food processing, utilizable in biosensors for detecting specific biomolecules or for contactless collection of impurities [7], thus contributing to medical diagnostics
- diagnostic imaging agents
- lipids extracted from used cooking oil, which can be changed to produce lipid-based nanoparticles for use as contrast agents in diagnostic imaging

- drug delivery systems
- pectin extracted from fruit peels, utilizable for drug delivery systems: pectin-based nanoparticles can encapsulate drugs and release them in a controlled manner
- nutrient extraction for cell culture
- nutrient-rich extracts from plant residues, utilizable as supplements in cell culture media to produce therapeutic proteins and vaccines
- collagen as key component in the extracellular matrix, can be extracted from animal by-products like bones and tendons and it is valuable for tissue engineering applications, such as creating scaffolds for regenerating damaged tissues
- wound healing materials
- chitosan (natural polysaccharide derived from chitin), which can be obtained from the exoskeletons of crustaceans such as shrimp, crab, lobster, and other shellfish, having antimicrobial properties and utilizable in wound dressings for promoting tissue regeneration
- tissue engineering and regenerative medicine: in this framework, biomaterials are mainly used to produce scaffolds, subsequently loaded with cells (even stem cells), which, after implantation in the human body, can promote the development of new tissues aiming to the reparation/restoration of damaged ones due to diseases or traumas; in particular, hydroxyapatite i.e., a main component of bone tissue - can be derived from organic wastes such as bones, fish scales, egg and mollusc shells, and in this article this particular application is below stressed.

3. Biomaterials in tissue engineering and regenerative medicine

Nowadays there is a constant increase of the demand for orthopaedic implants on a global scale, with the related market foreseen to almost double in the next 10 years (Figure 1).

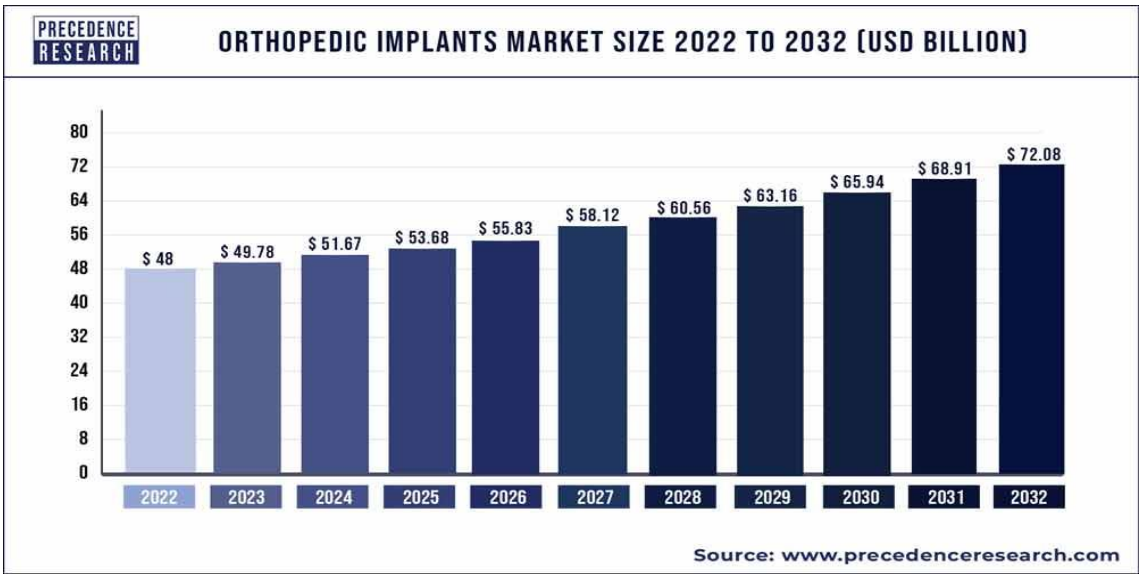

Figure 1. *Growth of global market of orthopaedic implants from 2022 to 2032 [8]*

This is particularly true in some Western countries, where a dramatic situation of denatality, which has been going on for several years now, is leading to a progressive ageing of the population (see, e.g., ref. [9] and Figure 2 for Italy), with a consequent increase in the number of people suffering from age-related orthopaedic diseases (primarily osteoporosis) and a greater likelihood of being subject to injuries and fractures.

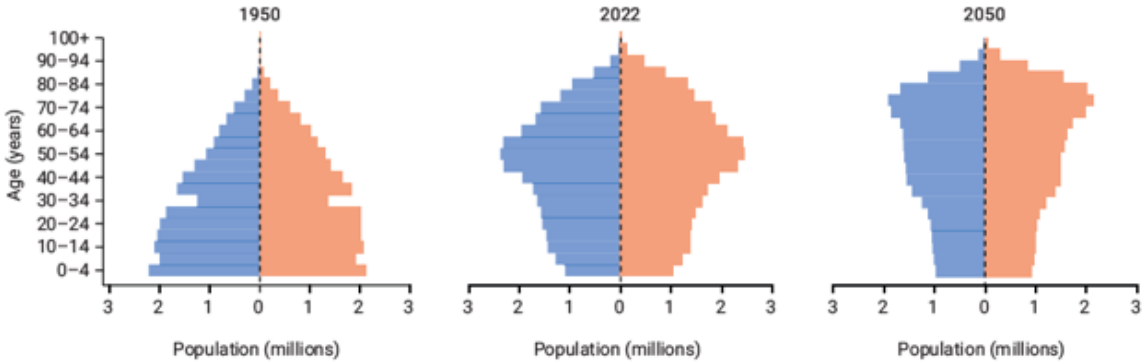

Figure 2. *Progression of population ageing in Italy (blue = males, orange = females)*

To fulfil this increasing demand, several classes of biomaterials have been studied and produced in the last decades, and the interdisciplinar research devoted to find new ones, with better performances both from the mechanical and the biological point of view, is now one of the most important branches of materials science.

Biomaterials can be divided into metallic and ceramic ones: the former include some stainless steels, various alloys based on Ti, CoCrMo, Pt, Ta and shape memory alloys (e.g., Nitinol); the latter include alumina, zirconia, calcium phosphates and hydroxyapatite (HAp). Metallic biomaterials, in general, have higher mechanical performances but poor biocompatibility, while the opposite holds for ceramics. In many medical applications, therefore, ceramic materials - also as composites reinforced with biopolymers such as collagen, chitosan, polylactic acid (PLA), polyglycolic acid and caprolactone - are often used as coatings on top of metallic prostheses.

In the following section, we will refer in particular to HAp and its production from food wastes. The chemical and structural characteristics of HAp are similar to the ones of bone and teeth [10], so that it is often employed as a bioactive coating for dental and orthopaedic implants, promoting the proliferation of osteoblastic cells on the prosthetic surface and therefore inducing the biological adhesion between bone and implant [11].

4. Hydroxyapatite from food waste

HAp is one of the main components of bone tissue, so that synthetic HAp is largely used in tissue engineering and regenerative medicine. Its stoichiometric formula is $Ca_{10}(PO_4)_6(OH)_2$ and, from the crystallographic point of view, it is arranged in a hexagonal packing with lattice parameters $a = b =$ 9.37 Å, c = 6.88 Å, $\alpha = \beta = 90°$, and $\gamma = 120°$.

The possible biomedical applications of HAp began to be studied during the 70’s, and since then the research in this field has been concentrated on trying to overcome several problems encountered when the pure material is implanted in the living tissues, mainly due to its poor mechanical properties in physiological environments, such as low strength, low toughness, low brittleness and low fatigue resistance. Several production methods have been tested in this period and, although the ideal performances have not been obtained yet, a very significant progress has been made. Nowadays, the principal production techniques to obtain synthetic HAp can be divided into three main groups: hydrothermal methods, sol-gel methods and precipitation methods; a detailed description of them can be found in [12].

In recent years, hand in hand with the development of technologies for the disposal of municipal waste, special attention has been paid to the possibility of obtaining biomaterials for tissue engineering applications from food waste. Concerning HAp, its extraction from various types of biowaste has been investigated, such as bones, eggshells and seafood shells ([13], [14], [15] and [16]).

Teoh et al. [17] obtained HAp from food waste chicken bones by boiling them in water, deproteinization in acetone and then calcination in a furnace at 1000 °C for 2 h to obtain pure phase hydroxyapatite powder. The microstructural features and mechanical performances were studied without and with adding pectin (extracted from lime peel), which is known to favour osteoblast proliferation and cell adhesion. Two different sintering procedures (i.e., conventional and two-step) were studied. Figure 3 shows the microstructure of the investigated samples, while their microhardness is shown in Figure 4.

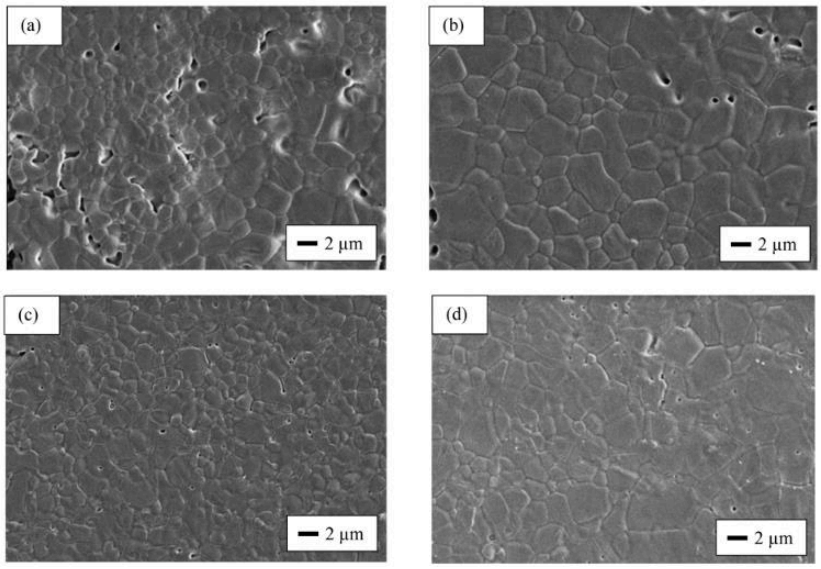

Figure 3. *SEM micrograph of HAp from chicken bones: a) pure HAp, conventional sintering, b) pure HAp, two-step sintering, c) HAp + pectin, conventional sintering and d) HAp + pectin, two-step sintering [17]*

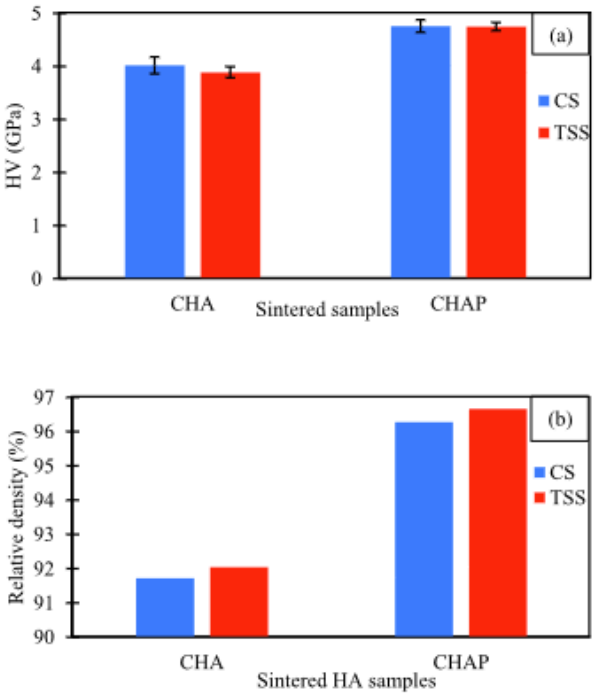

Figure 4. *Hardness (a) and density (b) of pure HAp from chicken bones: CHA = pure HAp; CHAP = HAp + pectin; CS = conventional sintering; TSS = two-step sintering [17]*

Mondal et al. [18] synthetized HAp from fish scale and used it to produce scaffolds to be implanted in a traumatized animal model (rabbit). The comparison with HAp obtained by a standard production method such as chemical precipitation showed a much better new bone cell formation, with good bio-affinity and osteoconductive characteristics (yellow arrow in Figure 5a). Cell infiltration occurs in the healing region also with HAp obtained by standard route, but with a much lower rate of recovery (Figure 5b). With respect to fish-scale HAp, the osteo-integration properties of HAp produced by chemical precipitation look much poorer.

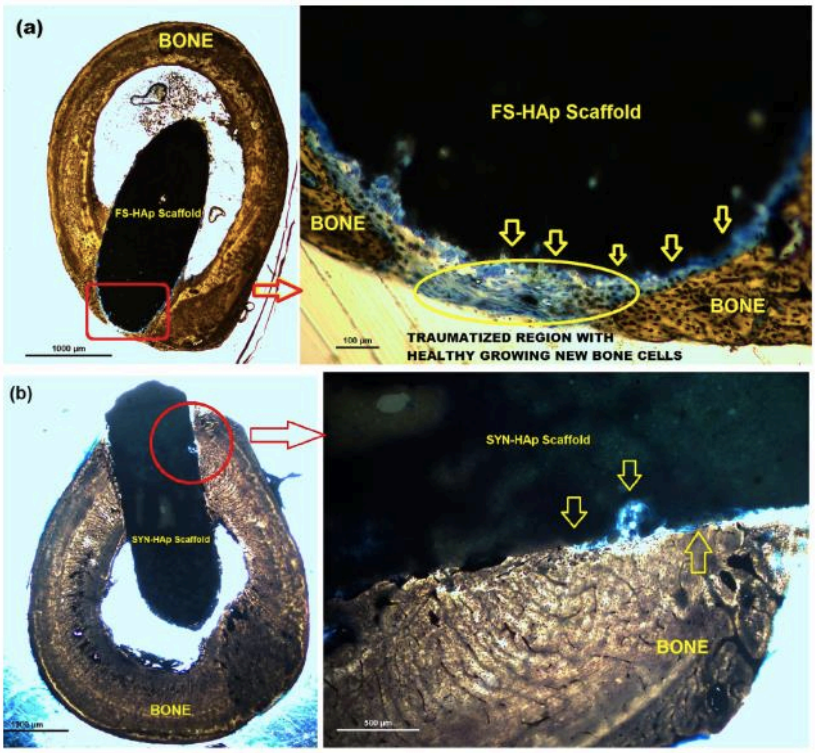

Figure 5. *Osteo-integration and new bone tissue formation on HAp scaffolds in the traumatized region of a rabbit animal model: (a) fish-scale HAp, (b) chemical precipitation HAp [18]*

Boudreau et al. [19] isolated HAp from the bones of Atlantic salmon processing waste, using a two-enzyme cocktail (i.e., Neutrase and Lipozyme CALB L). HAP products were classified as either pure sHAP or crude sHAP. Pure sHAP is the result of a successful enzymatic treatment in which all non-collagenous proteins and lipids are hydrolysed, while crude sHAP is the product of an unsuccessful enzymatic treatment. Figure 6 shows the XRD patterns obtained from raw salmon meat, pure sHAp and crude sHAp. Raw salmon meat shows a broad amorphous diffraction peak at 2θ = 19° that strongly decreases in crude sHAP and furtherly in pure sHAP, as the proteins and lipids of the meat are hydrolysed by the enzymes.

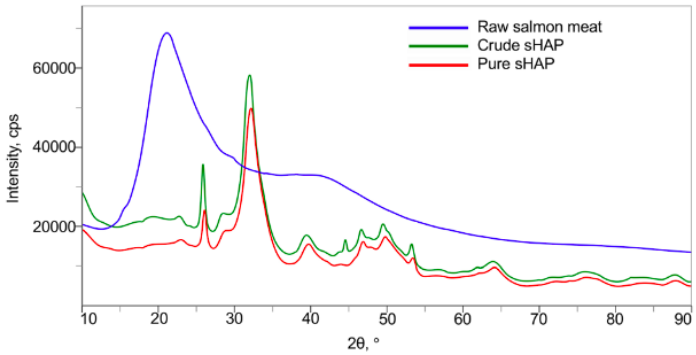

Figure 6. *XRD patterns of raw salmon meat, crude sHAp and pure sHAp [19]*

Nano-sized HAp was obtained from egg shells by Arslan et al. ([20] and [21]). The synthesis of HAp nanoparticles was carried out using three different methods, described in [20]. Figure 7 shows the TEM images of the three types of HAp nanoparticles obtained, as well as the related EDX microanalysis.

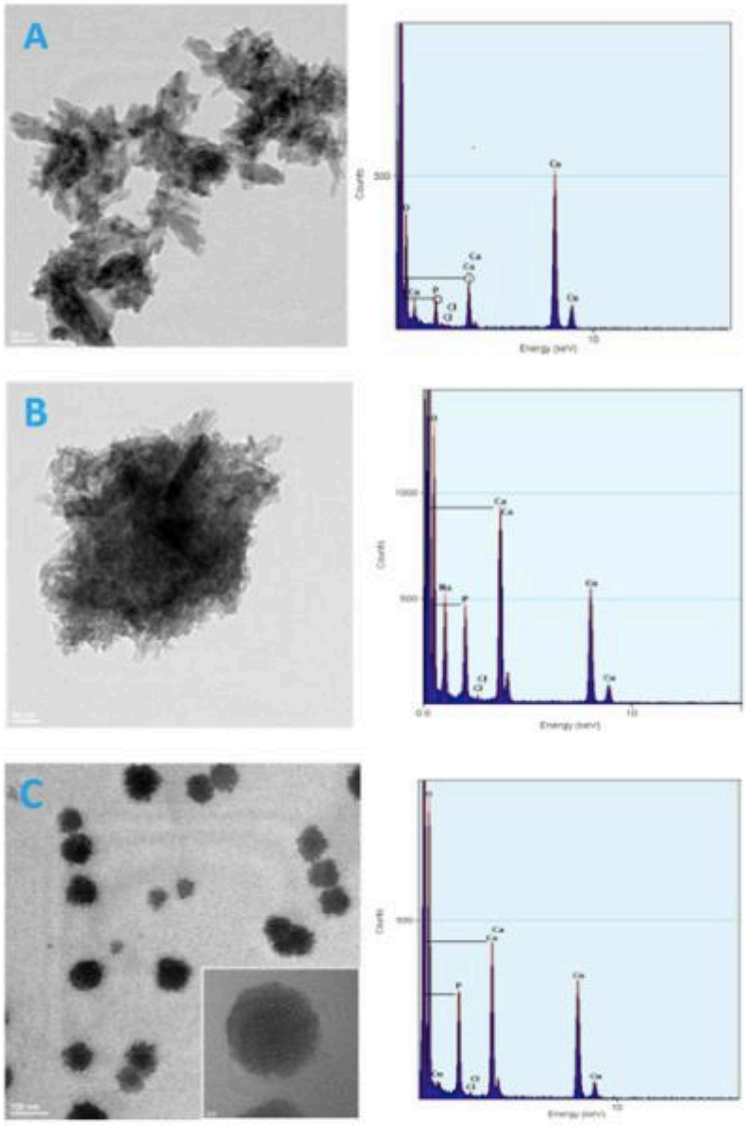

Figure 7. TEM images and EDAX spectra of HAp nanoparticles obtained by the three different methods described in [20]

5. Conclusions

The production of biomaterials from municipal wet waste contributes to waste reduction, more sustainable use of resources and mitigation of the environmental impact associated with traditional petroleum-based materials. Adequate information campaigns can be very useful to promote awareness of the environmental benefits of sustainable waste management and the use of biomaterials. In particular, the community must be appropriately involved in the separation of waste and in the recycling process. This work has been focused particularly to the production of hydroxyapatite from food waste, as the demand for this biomaterial, with many applications in orthopaedics and orthodontics, is foreseen to strongly increase in the very next years, also due to population ageing in some western countries. Examples taken from recent literature have been presented, also showing some advantages in terms of biological and mechanical performances with respect to the hydroxyapatite obtained from standard chemical routes.

References

[1] Chakrapani, G., Zare, M., Ramakrishna, S., 2022. Biomaterials from the value-added food wastes. Bioresource Technol. Rep. 19, 101181.
[2] Zabaniotou, A., 2018. Redesigning a bioenergy sector in EU in the transition to circular waste-based Bioeconomy-A multidisciplinary review. J. Cleaner Prod. 177, 197-206.
[3] Battistini, G., Ficoneri Bolasco, G., Fiori, F., Giampaoli, G., Martino, F., Pellei, B., Rogante, M., 2024. I biodigestori per il trattamento dei rifiuti organici offrono diversi vantaggi. Qualenergia, 2, 71-72.
[4] Mahabeer, G., Jin, S., 2024. Upcycling Food Waste into Biomaterials Applicable to Medical Products. Sustainability 16, 4473.
[5] Mapelli, F., Carullo, D., Farris, S., Ferrante, A., Bacenetti, J., Ventura, V., Frisio, D., Borin, S., 2022. Food Waste-Derived Biomaterials Enriched by Biostimulant Agents for Sustainable Horticultural Practices: A Possible Circular Solution. Front. Sustainability 3, 928970.
[6] Battistini, G., Ficoneri Bolasco, G., Fiori, F., Giampaoli, G., Martino, F., Pellei, B., Rogante, M., 2024. L'impianto biodigestore per il trattamento della frazione organica dei rifiuti urbani: caratteristiche e vantaggi d'impiego. INSIC – L’INformazione per la SICurezza. https://www.insic.it/tutela-ambientale/gestione-rifiuti/biodigestore-per-il-trattamento-dei-rifiuti-urbani-caratteristiche-e-vantaggi (accessed 04 September 2024).
[7] Novotný, P., Rulc, J., Divín, R., Pashchenko, A., Varga, J., Rogante, M., Varvařovská, L., Siroka, R., Jarosikova, T., Amler, E., 2023. Contactless collection of impurities on ultrasensitive nanofiber membrane, MTSM 2023, Split
[8] Orthopedic Implants Market Size, Share, and Trends 2024 to 2034, Precedence Research, CA, 2024. https://www.precedenceresearch.com/orthopedic-implant-market (accessed 04 September 2024).
[9] ISTAT, IT, 2021. Statistics report for IT. https://www.istat.it/wp-content/uploads/2021/11/REPORT-PREVISIONI-DEMOGRAFICHE.pdf (accessed 04 September 2024).
[10] Pokhrel, S., 2018. Hydroxyapatite: Preparation, Properties and Its Biomedical Applications. Adv. Chem. Eng. Sci. 8, 225-240.
[11] Kobayashi, M., Nihonmatsu, S., Okawara, T., Onuki, H., Sakagami, H., Nakajima, H., Takeishi, H., Shimada, J., 2019. Adhesion and Proliferation of Osteoblastic Cells on Hydroxyapatite-dispersed Ti-based Composite Plate. In Vivo 33(4), 1067-1079.
[12] Ma, G., 2019. Three common preparation methods of hydroxyapatite. IOP Conf. Ser.: Mater. Sci. Eng. 688, 033057.
[13] Szczes, A., Hołysz, L., Chibowski, E., 2017. Synthesis of hydroxyapatite for biomedical applications. Adv. Colloid Interface Sci. 249, 321-330.
[14] Fiume, E., Magnaterra, G., Rahdar, A., Verné, E., Baino, F., 2021. Hydroxyapatite for Biomedical Applications: A Short Overview. Ceramics 4(4), 542-563.
[15] Bee, S.L., Hamid, Z.A.A., 2020. Hydroxyapatite derived from food industry bio-wastes: Syntheses, properties and its potential multifunctional applications. Ceram. Int. 46(11), 17149-17175.
[16] Borciani, G., Fischetti, T., Ciapetti, G., Montesissa, M., Baldini, N., Graziani, G., 2023. Marine biological waste as a source of hydroxyapatite for bone tissue engineering applications. Ceram. Int. 49(2), 1572-1584.
[17] Teoh, M., Ng, C., Lee, S.K., Ramesh, S., Ting, C., Chuah, Y., Lim, I.Y., Tan, C., Sutharsini, U., 2024. Densification behaviors of hydroxyapatite/pectin bio-ceramics. Mater. Today Proc., in press.
[18] Mondal, S., Pal, U., Dey, A., 2016. Natural origin hydroxyapatite scaffold as potential bone tissue engineering substitute. Ceram. Int. 42(16), 18338-18346.
[19] Boudreau, S., Hrapovic, S., Liu, Y., Leung, A.C.W., Lam, E., Kerton., F.M., 2023. Isolation of hydroxyapatite from Atlantic salmon processing waste using a protease and lipase mixture. RSC Sustain. 2023(1), 1554-1564.
[20] Derkus, B., Arslan, Y.E., Emregul, K.C., Emregul, E., 2016. Enhancement of aptamer immobilization using egg shell-derived nano-sized spherical hydroxyapatite for thrombin detection in neuroclinic. Talanta 158, 100-109.

[21] Arslan, Y.E., Arslan, T.S., Derkus, B., Emregul, E., Emregul, K.C., 2017. Fabrication of human hair keratin/jellyfish collagen/eggshell-derived hydroxyapatite osteoinductive biocomposite scaffolds for bone tissue engineering: From waste to regenerative medicine products. Colloids Surf. B Biointerfaces 154, 160-170.

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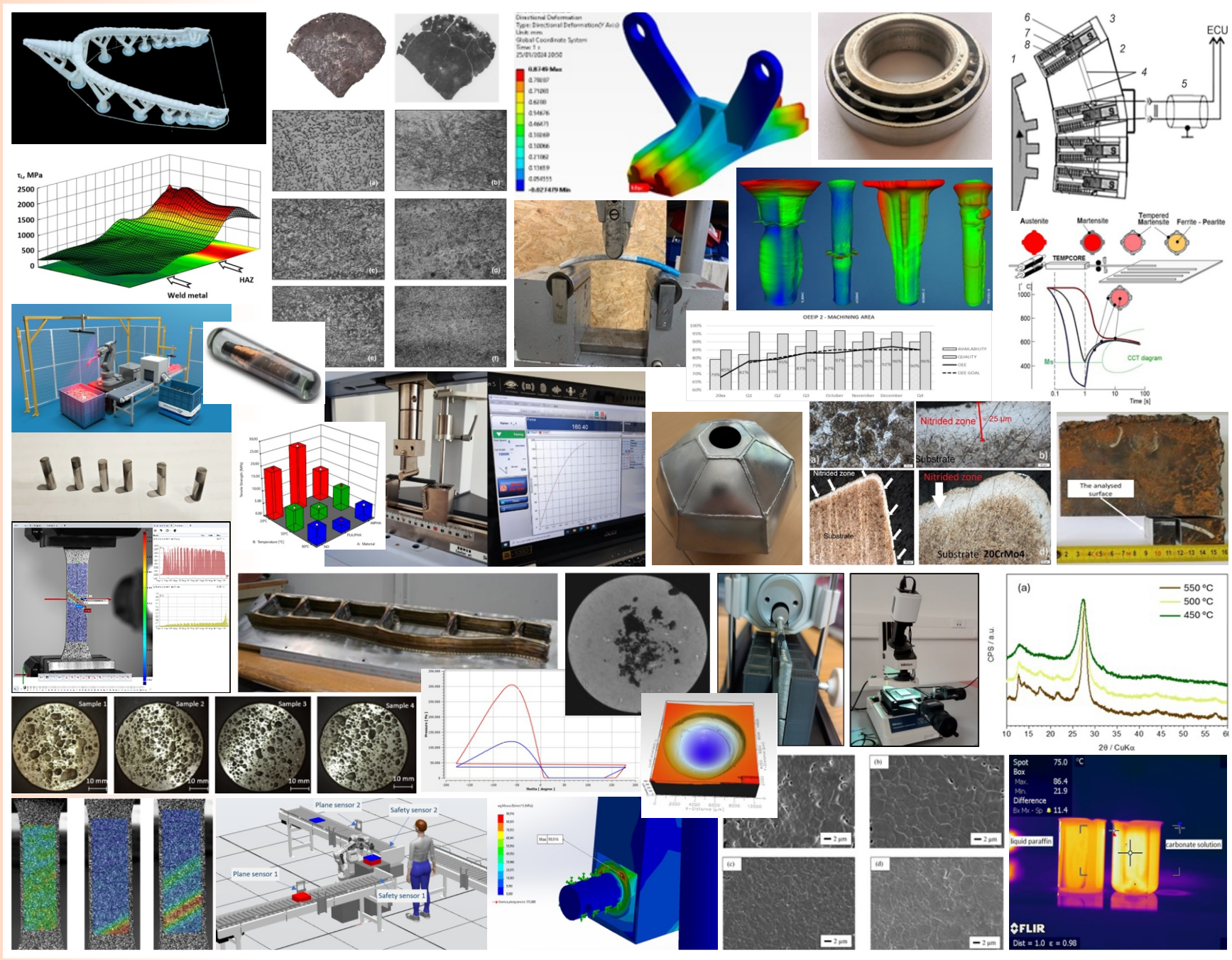

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