Original Article

Agricultural And Pharmaceutical Applications Of Eggshells: A Comprehensive Review Of Eggshell Waste Value-Added Products

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Abstract

The production of a huge number of chicken eggs towards the supplement of portentous food is a more ideal direction for sustainable economic growth and national development. Nonetheless, 90% of egg parts are used in food and the diet, while 10% are discarded as eggshell (ESs) components. Without proper disposal, ES-waste releases ammonia (NH_3), hydrogen sulphate (H_2S), and offensive odours to enhance the growth of harmful insects and bacteria, and is able to contribute to the contamination of soil, water, and the environment. Thus, based on global egg consumption rates (approximately 8000 million dozes in 2020), roughly 50,000 tonnes of solid ES waste with a high calcium content are generated. Well disposal methods or conversion to value-added products is the call of the day. After implementation of enriched research approaches, the calcium-rich ES-waste is now converted into more value-added products. Currently, ESs are widely used as alternative calcium supplements for human and animal feed. ESs would promote tissue and bone regeneration and be used as a rich mineral fertiliser in agricultural farming, pest control, soil pH control, and soil contamination removal. This review gathered a huge number of ES-based value-added applications and encouraged more research to explore the industrial benefits of ES-waste. ES is not a waste, but rather a cost-effective, environmentally safe, and economically advantageous raw material for the majority of sectors, according to the research documents, patents, and value-added goods that have been commercialised.

Keywords: Egg shells, ES-waste disposal and environmental issue, ES-based value-added products, agricultural and pharmaceutical applications of ES-waste

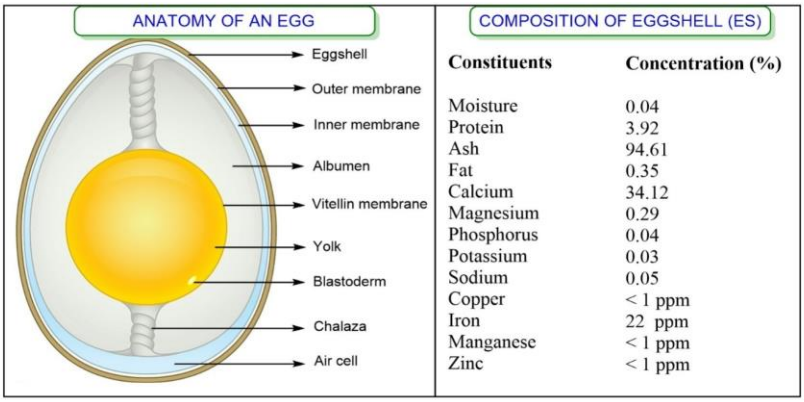
INTRODUCTION

An egg is a reproductive vehicle for avian and poultry species, where eggshell (ESs) plays a crucial role in protecting against physical and pathogenic barriers during the growth of those avian and poultry embryos (Hincke et al., 2012; Cordeiro and Hincke, 2016; Wilson et al., 2017; Hincke et al., 2019; Halgrain et al., 2022). In addition, ESs provide continuous metabolic and nutritional support without any obstacles to the end of incubation of chick hatching/pipping (Hincke et al., 2012; Athanasiadou et al., 2018; Stapane et al., 2019). On the other hand, chicken eggs are widely used as a proteinous and high-quality nutritious human diet in day-to-day life by all communities and age groups (Miranda et al., 2015; Réhault-Godbert et al., 2019). As a result of increased egg consumption and demand, global egg production has steadily increased from 74.14 to 86.67 million metric tonnes in the period 2019–2020 (FAO, 2021; Shahbandeh, 2022), and poultry egg products are now regarded as one of the most sustainable economic farming with a rich source of business for any nation. Among all, China, the United States, Indonesia, India, and Mexico are the world's leading egg production continents, producing approximately 63% (> 1653 billion eggs) of total global egg production (FAO, 2021; Shahbandeh, 2022).

About 90% of egg parts are used in food and diet, and the remaining 10% are discarded as ES components. Thus, based on global egg consumption rates (approximately 8000 million dozes in 2020), roughly 50,000 tonnes of solid ES waste with a high calcium content are generated annually (Waheed et al., 2022). The United States Department of Agriculture (USDA) estimation indicated that, the global egg consumption rate will reach up to 8917 million dozen by 2028 and accordingly the rate of ES waste also increased (Nyalala et al., 2021; Waheed et al., 2022). Without proper disposal or being discarded in landfill sites without any pre-treatment, ESs/egg waste releases ammonia (NH_3), hydrogen sulphate (H_2S), and offensive odours to enhance the growth of harmful insects and bacteria, and is able to contribute for the contamination of soil, water, and the environment (Mignardi et al., 2020; Nyalala et al., 2021; Rohmadi et al., 2021; Waheed et al., 2022). As a potential research field in agriculture or the poultry domain, several ES disposal methods and utilisation methods have been proposed (Konwar et al., 2019; Waheed et al., 2020; Girelli et al., 2020; Baláž et al., 2020; Mignardi et al., 2020) and some research is still going on to utilise those waste products on a large scale for agricultural and pharmaceutical applications (Ahmed et al., 2021; Ngayakamo and Onwualu, 2022). Proper disposal or converting this calcium-rich solid waste to some value-added applications though several patented techniques (Schmidt et al., 2017; Kenny et al., 2018; Blaine and Thang, 2019; Huang et al., 2020). Apart from agricultural and pharmaceutical applications, ES components are also used in several material science, tissue engineering, and industrial catalytic applications globally (Baláž et al., 2020; Mahdavi et al., 2021; Ngayakamo and Onwualu, 2022). Therefore, the present review focused on agricultural, pharmaceutical, and other applications as the transformation of ES waste to value-added products or reagents.

2. CHEMISTRY AND COMPOSITION OF ES

The outer part of an egg is called an ES, and it is attached by a thin layer of eggshell membrane (ESM) according to egg anatomy (**Figure 1**). Combinedly, the outer part is composed of two different parts: calcium carbonate ($CaCO_3$) and a proteinous eggshell membrane (ESM). In different time periods, several hybrids of chicken ESs were investigated, and all reports agree that the main component is $CaCO_3$ in the form of calcite at a range of 94–97% with Ca3(PO4)2 (1%), MgCO3 (1%), organic material (4%), etc. (Stadelman, 2000; Hunton, 2005; Rose and Hincke, 2009). Apart from inorganic constituents in ES, the ESM purely contains organic characters in the form of different proteins, amino acids (mostly proline, glutamic acid, and glycine), etc. (Zhao and Chi, 2009; Hincke et al., 2012; Kaweewong et al., 2013). However, the composition, quantity, and colour of ESs varied depending on the type of poultry or avian species (Nakano et al. 2003). Anyway, to convert sustainable value-added applications is the global call to utilise large scale calcium-rich solid waste ESs.



Constituents	Concentration (%)
Moisture	0.04
Protein	3.92
Ash	94.61
Fat	0.35
Calcium	34.12
Magnesium	0.29
Phosphorus	0.04
Potassium	0.03
Sodium	0.05
Copper	< 1 ppm
Iron	22 ppm
Manganese	< 1 ppm
Zinc	< 1 ppm

Figure 1. Graphical presentation of anatomy of an egg and composition of eggshell (ES).

3. VALUE-ADDED APPLICATIONS OF CALCIUM RICH ES SOLID WASTE

Generally, calcium carbonate (ground/precipitated) is an essential raw material for most of the agricultural, pharmaceutical, and other manufacturing industries (Laca et al., 2017; Seifan and Berenjian, 2018; d'Amora et al., 2020; Song et al., 2022). As per the report, the global market for calcium carbonate may reach $ 44.5 billion in 2022 and is expected to grow at a compound annual growth rate of 5.4 % from 2020 to 2030. Although the demand for calcium carbonate slightly decreased in 2020 due to the coronavirus pandemic, it again increased the demand mostly for food packaging, hygiene-related, and medical specialty sheet applications (Anonymous 2022). Therefore, the calcium-rich ES waste could be a sustainable replacement and fully fulfil the demand for calcium carbonate to be used as a raw material for calcium carbonate (limestone), soil conditioners, food additives or supplements, biomaterial, cosmetic or pharmaceutical base, catalyst, and wastewater purifiers (Waheed et al., 2020; Mignardi et al., 2020; Owuamanam and Cree, 2020; Song et al., 2022). ES waste could be used to replace the extensive use of natural resources in a lot of biological, chemical, and engineering applications (**Figure 2**). Nevertheless, herein, we have concentrated more on ways to employ ES waste in profitable agricultural, pharmaceutical and other industrial applications.

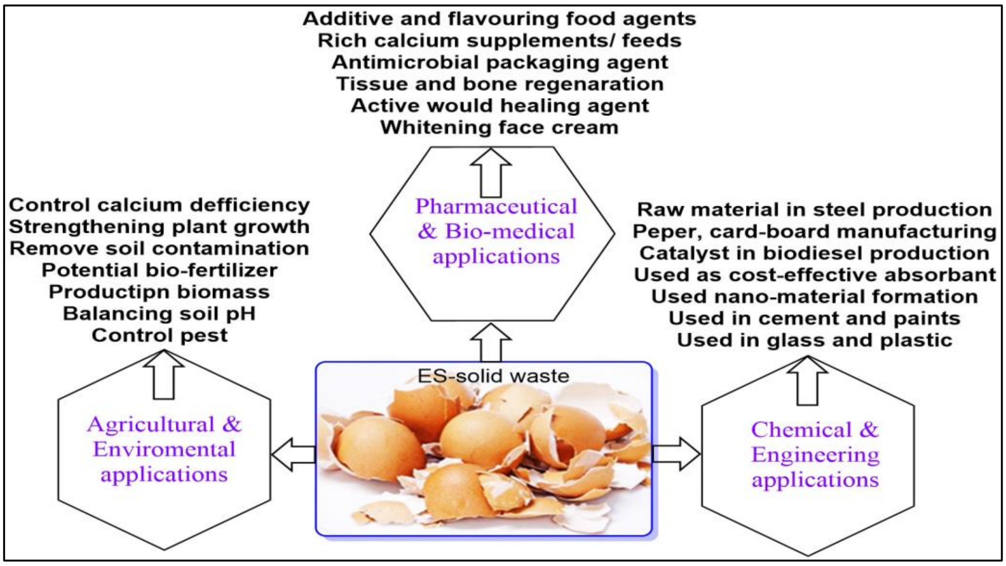


Figure 2. A broad-spectrum application of ES-solid waste to the transformation of value-added by-products.

3.1. Agricultural and environmental applications of ESs

The crushed ESs are rich sources of calcium carbonate, including potassium, phosphorous, and magnesium. These are essential minerals for strengthening plant cell walls and root growth. In addition, ESs are used as suitable agents in seed germination pots for large scale garden farming, help to avoid the blossom-end rot in tomato fruits (a black spot at the end of the tomato fruit) by overcoming calcium deficiency, controlling pests like snails and slugs, and balancing soil pH for good agricultural farming (Oliveira et al., 2013; Ahmed et al., 2021). Technically, being a rich source of calcium, crude ESs increases the calcium level in the soil and that rich calcium level enhances the uptake of minerals and nutrients via roots and also decreases the soil acidity level. Therefore, crude ESs are an efficient and affordable bio-fertilizer for specific indoor and outdoor gardens, farming, and home plants. Additional research is being done to discover whether this calcium-rich waste is suitable for all plants (Ahmed et al., 2021; Carmona et al., 2022).

Briefly, **c**alcium oxide (CaO) is used as a soil amendment agent to supply calcium to agricultural land for crops, which is basically extracted from limestone, oyster shells, chalk, etc. At the same time, ESs are a substantial source for CaO extraction via the calcination method. CaO was widely used as a neutralising agent in agricultural farming to balance the pH of soil, soil bacteria, and microflora for cost-effective soil fertility (Ahmed et al., 2021). Some recent studies have also shown that CaO in nano form can be useful in soil contamination, specifically in the removal of arsenic-like toxic heavy metals in agricultural land (Ramrez-Rodrguez et al., 2020; Nazir et al., 2022).

Similarly, agricultural farming is adopting newer protocols towards enhancement of food demand and harvesting, where nano-fertilizer is one of the potential approaches. Thus, calcium phosphate ($Ca_3(PO_4)_2$) in nano-form is considered a potential macronutrient nano-fertilizer with superiority to conventional products due to its nanometric porous size, having been functionalized with additional macronutrients like urea by advantageous nitrogen-releasing and water solubility profiles (Carmona et al., 2022). In addition, as a rich source of calcium, ESs are also used as an additive source of well-digested animal feeds for poultry. Overall, there is lots of work going on, and hopefully, ESs could be considered as potential waste or alternative raw material for most of the industry.

3.2. Pharmaceutical and bio-medical applications of ESs

Similar to the agricultural sector, calcium is also a vital component in most pharmaceutical applications. Calcium compounds such as calcium carbonate, calcium citrate, calcium phosphate, calcium chloride, etc., are also widely used in biomedical, nutritional, and pharmaceutical sectors (Singh et al., 2021; Ahmed et al., 2021). Commercial calcium supplements are typically made from dried shrimp, fish, oyster shells, corolla, and algae (Lu et al., 2022); however, recent research has found that ES is a more ecologically and economically sustainable source for animal feed and human health applications (Brun et al., 2013; Bartter et al., 2018; Lewicka et al., 2020). Several investigations also indicated that ES was a wealthier source for calcium extraction than oyster shell waste (Chakraborty and Gaonkar, 2016).

As per investigations, ESs could be used as alternative sources of calcium tonic and food additive agents in the form of calcium lactate, calcium propionate, calcium gluconate, calcium citrate, etc., for both the medicinal and cosmetic sectors (Singh et al., 2021; Ahmed et al., 2021). In its calcium lactate form, ES calcium is good in solubility with an absorption profile and is widely used in the pharmaceutical industry as a flavouring nutrient and an additive antimicrobial agent in hygienic packaging (Huang et al., 2019; Chen et al., 2019). Still, there are several patented methods for the extraction of calcium lactate from ES (Ahmed et al., 2021). The functionalized mixture of ES with peanuts, sesame extracts, enzyme mixture (1% protease, 5% amylase, and 2% pectase) with chitosan and alginate proved to be a potential, cost-effective, biodegradable, and easy absorption dressing material (Ye et al., 2019). Different methods are used to extract calcium citrate from ES, which is then used in a variety of medicinal purposes (Waheed et al., 2019).

Similarly, the calcium phosphate market also reaches up to 900 million by 2025, where ES could be considered as a potential alternative resource for extraction (Ahuja et al., 2019; Xu et al., 2020). Due to their high biodegradability and biocompatibility properties, two forms of calcium phosphate, namely, tri-calcium phosphate (β-TCP) and hydroxyapatite (HAP) have been widely used as essential minerals for the make-up of hard tissues like teeth, bone, and the fabrication of artificial bone for biomedical applications (Quina et al., 2017; Lee, 2018; Lee and Kang, 2019). In addition, ESs-derived composites are used in skin whitening, exfoliating, and moisturising agents in place of polypropylene and polyethylene, which contain hazardous materials in several commercially available whitening facial creams (Zhang et al., 2018). Overall, ES could be considered an attractive raw material for supplementary for most pharmaceutical and biomedical applications (Singh et al., 2021; Ahmed et al., 2021).

3.3. Other potential applications of ESs

Towards highlight of other applications ES, > 50 % of geological calcium carbonate or limestone was used for steel manufacturing and rest of calcium carbonate used in building, construction, water treatment, agriculture, paper, plastics and paint (Limestone, 2019; Lewicka et al., 2020; Ahmed et al., 2021). The commercially available limestone powder is around 200-350 dollar/ metric ton and on an average 88 to 270 kg limestone is used for production of every ton of crude steel. As per World Steel Association report, 1870 million metric tons of steel were manufactured in 2019 (Katsuyama et al., 2005; Mordor Intelligence, 2020). Thus, it is clearly indicated the size of calcium carbonate demand/ market, where ES waste can play in major role in coming years.

Similarly, calcium carbonate is another essential material for paper manufacturing and the production of paper and paper board word wide is 401 metric ton as market size 351.53 billion dollar. In general, around 385 kg of filters ($CaCO_3$) and coating pigments ($CaCO_3$ and kaolin) are used for every ton of paper production (Lewicka et al., 2020). Thus, ES waste also a good market to use in paper industry (Limestone, 2019; Tiseo, 2022). Treatment of toxic-polluted water, limestone also used through hydroxyapatite. Mainly the transformation of ES to ES-based hydroxyapatite on industrial prospective is five time cheaper and a cost effective than the existing toxic disposal method (Mignardi et al., 2020). The value of neutralised quicklime (CaO) is now 124 dollars per ton, and it is widely used in the manufacture of flat glass, crystal glass, and glass container (5 to 12% CaO is required for each glass product) (Lewicka et al., 2020). Thus, ES could be a good raw material for CaO extraction. In addition, ES could be used as a catalyst to produce more biodiesel, and more refinement of the method is going on (Xiang et al., 2018).

4. FUTURE PROSPECTIVE OF ES IN VALUE-ADDED PRODUCT DEVELOPMENT

ES waste increased significantly in response to protenious food demand and egg consumption in day-to-day life. Thus, management of such calcium-rich solid waste through recycling into value-added products is essential. On the other hand, the transformation of ES like daily wastes to be utilised into value-added agents in agriculture, health, and pharmaceutical industries is called for from a sustainable nation building point of view. According to reports, up to 30% of ES is still used in medical and pharmaceutical products such as calcium supplements, antibacterial additives, flavouring, wound dressing, bone or tissue regeneration, and whitening face creams. Similarly, in agricultural and other industrial applications in the form of biofertilizer, removal of soil contamination, pest control, glass, plastic, cement, and paint industry with biodiesel production, proved that ES could not be a waste and is now an essential raw material for most industries through most of the novel research investigation. Thus, more research may help to utilise 100% of ES waste in value-added products in future endovers.

From ES-based value-added products, calcium supplements in the form of human, animal, and agricultural feeds is a sustainable sector for ES waste. Bone Health OriginalTM capsules are a value-added optimised formulation with a high calcium and vitamin D3 content that is easily digestible for bone health. Similarly, OVOCETR or EGGNOVO is another ES-based marketed product and a supplementary source of highly absorbable calcium for both human and animal consumption (EGGNOVO), Eggshell Calcium Supplement™ or irRAWsistible is recommended for the pet. Similarly, Cluster BusterR is an eco-friendly ES-based power used to capture flies and Powder Trapr as patented formulae available on the market for insect pests. As mentioned above, research papers, patents, and commercial products show that ES trash has the potential, alternative, and economics to produce more value-added products and offer a fresh approach to the growth of a sustainable nation.

5. CONCLUSION

Chicken eggs are widely used as a proteinous and high-quality nutritious human diet for all communities and age groups. From each consumed egg, 10% of eggshell (ES) waste is generated. A huge quantity of that waste has been generated by hotels and restaurants, fast food shops, centres, bakeries and food processing units on a daily basis. Proper disposal of such calcium-rich ES waste is expensive and creates more environmental issues. Thus, in the 21st century, research on waste to value-added products is the main aim, where ES-waste is also an issue to be solved through advanced research. Indeed, targeted research has greatly aided in the transformation/production of a greater number of value-added products by utilising ES-waste. Currently, ES-waste is used in most agricultural, pharmaceutical, biomedical, environmental, and engineering applications and is considered a cheaper, eco-friendly calcium raw material. Thus, this brief review on ES-waste-based value-added applications inspires academic and industry researchers to work more on poultry waste for the sustainable growth of the nation and to fully filament the daily demand for food, clothes, and shelter through the growth of agriculture, biomedical, pharmaceutical, and engineering sectors. Overall, waste management is a one of the major research areas in the poultry sector at present.

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