

Review

Nitrogen and Phosphorus Removal from Wastewater Using Calcareous Waste Shells—A Systematic Literature Review

Kien Tat Wai ¹, Aisling D. O'Sullivan ^{1,2}  and Ricardo Bello-Mendoza ^{1,*} 

¹ Department of Civil and Natural Resources Engineering, University of Canterbury, Private Bag 4800, Christchurch 8140, New Zealand; kientat.wai@canterbury.ac.nz (K.T.W.); aisling.osullivan@canterbury.ac.nz (A.D.O.)

² Centre for Ecological Technical Solutions (CELTS), University of Canterbury, Private Bag 4800, Christchurch 8140, New Zealand

* Correspondence: ricardo.bellomendoza@canterbury.ac.nz

Abstract: Nitrogen and phosphorus in freshwaters are a global environmental challenge. Concurrently, the shellfish industry's calcareous waste shells (CWSs) amount to ~10 million tonnes annually. CWSs can effectively adsorb dissolved pollutants, including nutrients, from water, which has motivated a growing number of experimental studies on recycling CWSs in wastewater treatment. This comprehensive literature review summarises and critically assesses the effectiveness of using different CWSs for removing nutrients from water. The effects of CWS type, initial pollutant concentration, adsorbent dosage, particle size, and contact time (CT) are investigated. The results show that phosphorus removal has been examined more than nitrogen. Most studies have been conducted using synthetic wastewater under laboratory conditions only. There is a large variability in experimental conditions, such as CWS adsorbent dosages (0.1–100 g/L) and CT (0.083–360 h). The calcination of CWSs is frequently used to enhance adsorption capacity. The Langmuir isotherm model has been found to fit adsorption data best when raw oyster shells are used, while the Freundlich isotherm is best when the adsorbent is calcinated mussel shells. The pseudo-second-order (PSO) kinetics model tends to describe adsorption data better than the pseudo-first-order (PFO) model in all shell types. There is significant potential for using calcareous waste shells to remove nutrients from wastewater in line with circular economy aspirations.

Keywords: nutrient removal; mussel shell; oyster shell; eggshell; adsorption; calcination; kinetic



Citation: Tat Wai, K.; O'Sullivan, A.D.; Bello-Mendoza, R. Nitrogen and Phosphorus Removal from Wastewater Using Calcareous Waste Shells—A Systematic Literature Review. *Environments* **2024**, *11*, 119. <https://doi.org/10.3390/environments11060119>

Academic Editor: Jan Vymazal

Received: 11 April 2024

Revised: 30 May 2024

Accepted: 2 June 2024

Published: 6 June 2024



Copyright: © 2024 by the authors. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license (<https://creativecommons.org/licenses/by/4.0/>).

1. Introduction

Nutrient pollution is the current primary cause of water quality impairment globally [1]. Persistent and excessive nitrogen and phosphorus inputs to freshwater systems lead to eutrophication. This is typically caused by rapid urbanisation [2,3], discharges from under-performing wastewater treatment systems [4,5], and excess fertiliser runoff from agricultural intensification [6–8]. As a result, excessive algal growth and dissolved oxygen depletion occur, causing an imbalance in aquatic ecosystems and diminishing freshwater resources [9,10]. Concentrations of 0.1 mg/L of phosphorus [5,11] and 2 mg/L of nitrate [12] are sufficient to cause freshwater eutrophication. The USEPA especially recommends a chronic criterion concentration of 2.4 mg of NH_4^+ /L at pH 7 and 20 °C for a 30-day average duration, not to be exceeded more than once every three years on average [13]. For comparison, the maximum allowable nitrate and ammonium concentrations in drinking water specified by the World Health Organization (WHO) are 40 mg/L and 0.2 mg/L, respectively [14].

As freshwater nutrient challenges are escalating, wastes from seafood processing industries are concurrently increasing. In 2020, the commercial shellfish industry was estimated at 42.6% of global seafood production by the UN's Food and Agriculture Organization (FAO) [15]. Shellfish and crustacean aquatic products comprise 70% calcareous

shells, with the remaining 30% comprising edible meat [15]. In New Zealand alone (pop. ~5 million), a Pacific Island nation, commercial fishing and aquaculture industries generated NZD 2 billion (0.7% of the country's GDP) in 2019 [16]. Of this, approximately 100,000 tonnes/year of green lip mussels were processed for meat, with the shells becoming waste material requiring disposal [17]. The New Zealand aquaculture sector is projected to grow from NZD 600 million in 2019 to NZD 3 billion by 2035, and other countries are similarly growing their shellfish production, so finding new ways of reusing and valorising CWSs will become critical to supporting more sustainable aquaculture [15,18,19] and aligning with aspirations to adhere to the sustainable development goals.

Various methods have been identified for removing nutrients from wastewater, including adsorption, chemical precipitation, ion exchange, biological removal, electrodialysis, and reverse osmosis [8,10,20]. The use of inexpensive adsorbents is becoming increasingly common because of the relative ease of their use, high efficiency, and low cost [7,8,19]. One such adsorbent is waste-shell-derived materials, specifically calcareous waste shells (CWSs), gaining momentum as wastewater treatment filter media [21]. Calcareous shells are composed of ~95% calcium carbonate [22]. Sources include oysters, cockles, mussels, clams, snail shells, eggs [21], and sea urchins (known in New Zealand as kina) [23,24]. Studies report a calcium carbonate content of 94–96% in egg shells [25–27], 90–97% in oyster shells [15,28,29], 95–96% in green mussel shells [15,30], 87% in zebra mussel shells [31], and 91% in kina shells [23,32]. Most studies reported thermal pretreatment (i.e., calcination or pyrolysis at 500–1000 °C) of the CWSs to increase their reactivity before use in wastewater treatment [19,33]. Calcination above 500 °C converts calcium carbonate to calcite and beyond 800 °C to calcium oxide [4,6,28].

The use of CWSs to treat various wastewater pollutants has grown over the last few years. Morris et al. [33] and Nguyen et al. [18] treated commercial dyes and heavy metals, finding that Zn^{2+} was more easily removed than Pb^{2+} and Cd^{2+} . Nutrient removal using CWSs has also been studied, with phosphorus removal attributed to adsorption and/or precipitation [4,6,34] and the removal of nitrogenous compounds, such as ammonium (NH_4^+) and nitrate (NO_3^-), attributed to chemisorption [18,35,36] or physisorption [10]. In most of the studies that trialled CWSs as an adsorbent [20,37,38], the calcination of CWSs at 500–1000 °C was applied to increase their reactivity [19,33]. Depending on the CWS calcination temperature and the reaction product formed, phosphate is removed via adsorption on calcite [6], or by precipitation as calcium phosphate when phosphate ions react with calcium ions from the dissolution of calcium oxide in water [39]. However, Nam et al. [40] found that hydrated calcinated oyster shells did not significantly remove nitrogen, due to the high solubility of nitrogen compounds compared to the near-complete phosphorus removal via alkaline precipitation at pH 12.

Bhatnagar and Sillanpää [41] reviewed nitrate removal from wastewater using different adsorbents but did not include CWS adsorbents, focussing more on activated carbons, clay-based adsorbents, double-layered hydroxides, zeolites, agricultural waste materials, and industrial wastes. Recent review papers have discussed valorisation opportunities for CWSs from snail shells [42] and molluscan shells in wastewater treatment [43], and other shell wastes, i.e., bivalve shells [44], egg shells [45], and general shellfish waste [15], in multiple applications in agriculture, construction, environmental protection, biomaterials, and food additives. Hart [21] also provided a mini-review on the properties and various applications of waste shells in wastewater treatment, cement production, building construction aggregates, biomedical manufacturing, and industrial catalysts. Eggshells have been used in a broad range of applications including in polymer, metal, and ceramic composites, as evaluated by Vandeginste [45]. Wan Mahari et al. [46] reviewed studies that used CWS biochar as an adsorbent in removing emerging pollutants from aquaculture wastewater. The conversion of large amounts of widely available CWSs from the food industry, such as eggshells, into useful resources contributes to reducing, reusing, and recycling this waste and, thus, to the circular economy. Despite these reviews on CWS valorisation opportunities, there is no comprehensive review on the use of CWSs to re-

move nutrients from wastewaters. This comprehensive, systematic review was therefore undertaken to synthesise and critically assess the current knowledge and research gaps in using CWSs as an adsorbent to remove nitrogen and phosphorus from wastewater. The main objectives are to (i) synthesise the literature on nutrient removal from wastewaters by CWSs; (ii) summarise the nutrient removal mechanisms, isotherm, and kinetic models in the studies; (iii) examine the effects of operating parameters (wastewater type, adsorbent dosage, contact time, pH, pollutant concentration, and particle size) on nutrient removal; and (iv) highlight knowledge gaps and future directions for the successful use of CWSs as an adsorbent for water nutrient removal.

2. Materials and Methods

A comprehensive search of the scientific literature published from 2010 to 2022 was conducted using Scopus and Compendex databases. Scopus is an extensive, multidisciplinary, bibliographic database, and its use has been widely reported for systematic literature reviews [47–51]. Burnham [52] also stated that Scopus is preferred to the Web of Science (WoS) due to its higher indexed citations and daily database updating. Scopus provides a broader and more inclusive content coverage in the engineering, chemistry, environment, and general sciences, with easier open access to authors [52,53].

The screening of the literature included searching for key terms in the title, abstract, and keywords. Terms included calcareous shell, mussel shell, oyster shell, clam shell, eggshell, or bivalve shell (Step 1, Figure 1). Literature types were confined to journal articles and conference papers (Step 2, Figure 1) for the last decade (2010–2022) and published in English (Step 3, Figure 1). Keywords were then filtered to nitrogenous and phosphorus compounds (Step 4, Figure 1), including wastewater (Step 5, Figure 1). Next, the search criteria focussed on the treatment or removal of those pollutants using CWSs (Step 6, Figure 1). Finally, manual screening excluded articles about other pollutants such as heavy metals, bacteria, or soil (Steps 7 and 8, Figure 1).

After this screening process (Figure 1), three specific criteria were applied in Step 9 (Figure 1) to refine the search further: (i) Does the study investigate nutrient removal from wastewater using CWSs? (ii) Does the study report pollutant removal capacity? (iii) Does the study discuss the possible removal mechanisms, isotherm, and kinetics? Once all these three criteria were satisfied, the total number of publications analysed in detail was 64 (Step 10, Figure 1). Relevant information from these publications was then extracted into a custom-built Excel spreadsheet and grouped into different tables and figures for data analysis and interpretation. Further data analysis involved the use of OriginPro 2024b software for data presentation in a box plot and Pearson's correlation.

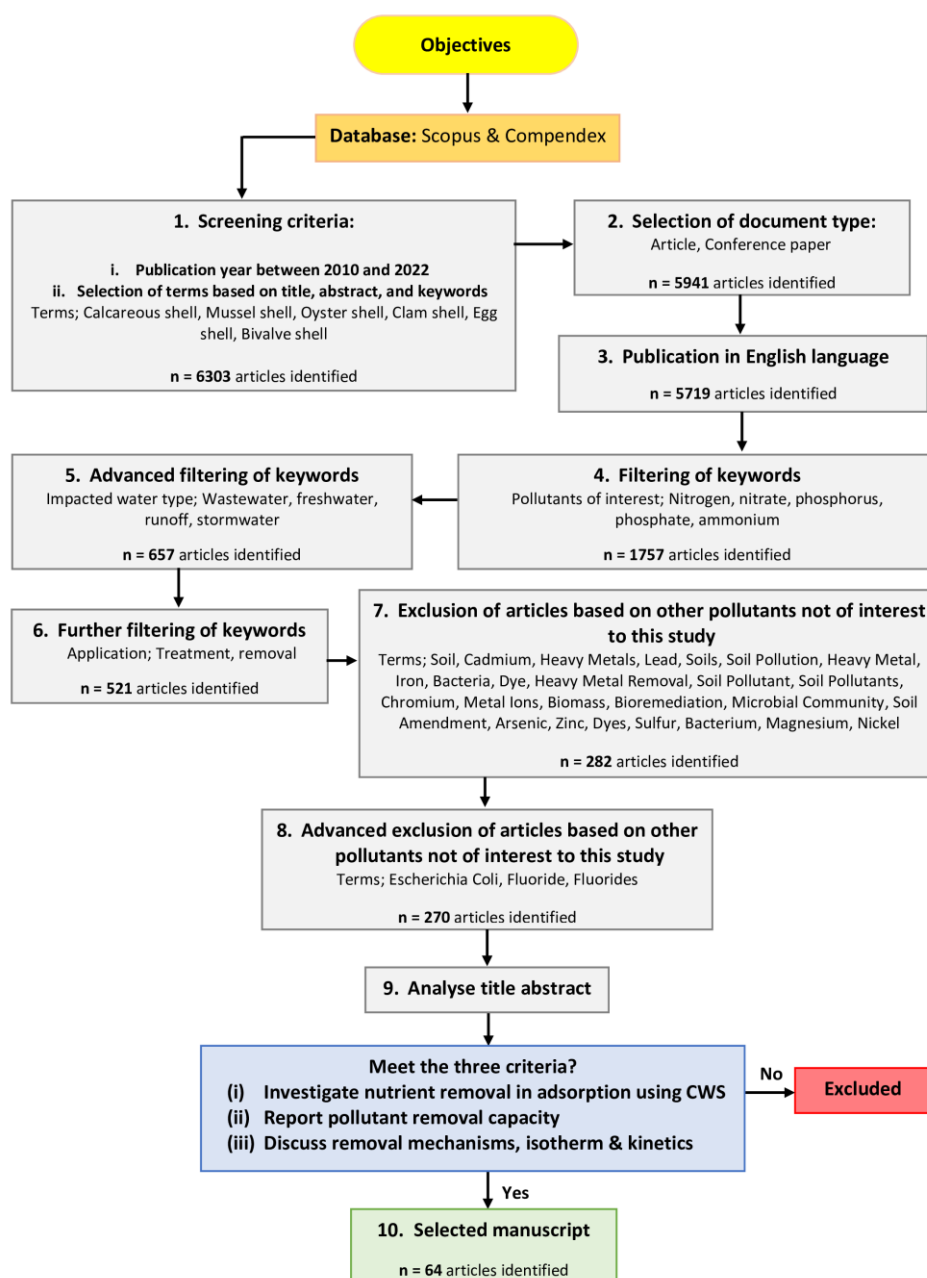


Figure 1. Literature retrieval and screening process for the review (97% journal articles and 3% conference papers).

3. Results

Table 1 summarises the CWS types, Common (English) and Scientific (Latin) names of the animal shell, wastewater type, and nutrient pollutant form, along with citation(s) for each study. Of all CWS types used to treat nutrients in wastewater, oyster shells (OSs) were reported most frequently ($n = 25$, 39%), followed by mussel shells (MSs) ($n = 19$, 30%) and eggshells (ESs) ($n = 12$, 19%). Shell availability, repurposing potential, and the desire to align with the circular blue bioeconomy are the main reasons cited for these shells' use [19,30,54]. Fewer studies investigated other CWS types: these included clam shells (CSs) ($n = 3$, 5%), mixed/combination of shells (CoS) ($n = 3$, 5%), bivalve shells (BSs) ($n = 1$, 1%), and zebra mussels (ZSs) ($n = 1$, 1%). Some CWSs were studied due to their abundance in a particular region [55–58] or, in the case of zebra mussel shells, due to their invasive presence in a lake [31].

3.1. Regional and Temporal Trends

Most publications (53%, $n = 34$) originate from China and Malaysia (Figure 2a). This may be a reflection of the sheer volume of scientific publications emerging from China (in particular) with a large population and active research community [59]. Additionally, it may be because these (and other cited countries such as Brazil, Japan, Malaysia, South Korea, Taiwan, and Vietnam) have long coastlines with booming marine farms, and hence have an interest in valorising abundant seashell waste [15,33,37,42,60]. There has been a sharp increase in the number of studies using CWSs to treat nutrients since 2015 (Figure 2b), with this trend expected to continue because of the increased global awareness of freshwater pollution [19] and CWS waste valorisation opportunities [7,36]. Furthermore, there has been a recent trend to investigate CWS biocomposites for the purpose of removing nutrients from wastewater, such as testing eggshell and potato peel [27], oyster shell and rice husk biochar [28], oyster shell and tobacco straw biochar [61], and eggshell and palm mesocarp fibres [62].

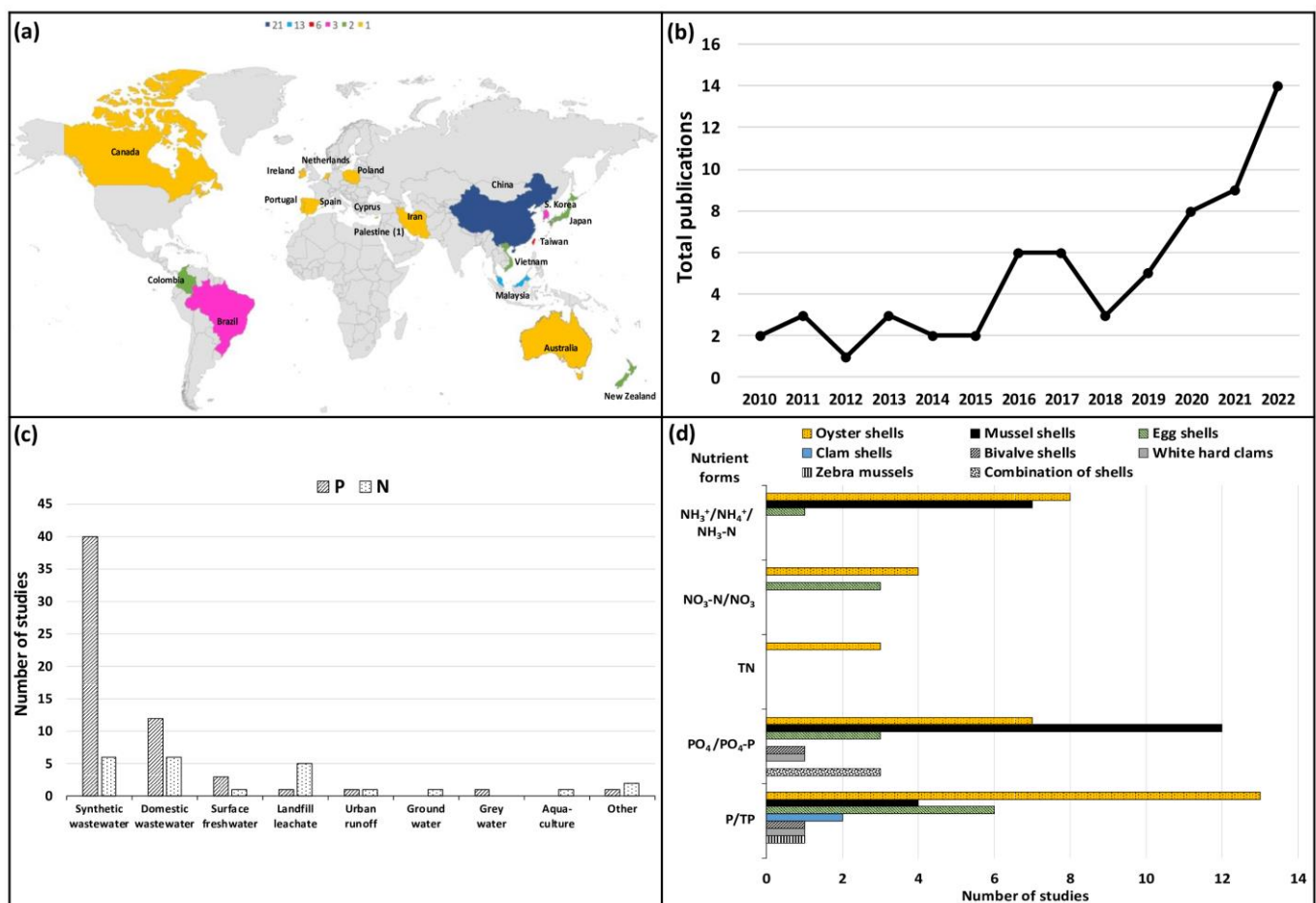


Figure 2. Number of publications by (a) country, (b) year, (c) wastewater type, and (d) nutrient forms. Total (n) of publications = 64 (Figure 2a,b); 59 for P and 23 for N (Figure 2c); 81 (Figure 2d). The total number of studies (81) across all wastewater forms in Figure 2d is greater than the total number of publications (64) because some studies reported multiple nutrient pollutant forms within the same study. Palestine (1) refers to 1 publication.

Table 1. Studies using calcareous waste shells (CWSs) to treat nutrients in wastewater.

CWS Type	Common (English) Name	Scientific (Latin) Name	Wastewater Type and Target Pollutant			Reference
			Domestic/Municipal Wastewater	Synthetic Wastewater	Other Wastewater	
Mussel shells	Mediterranean mussel	<i>Mytilus galloprovincialis</i> Lamarck	PO ₄ ^{3−} , NH ₄ ⁺ (treated domestic wastewater effluent), PO ₄ ^{3−} (municipal)	PO ₄ ^{3−}		[63]
				P		[64]
				NH ₄ ⁺		[8]
				PO ₄ ^{3−}		[18]
				PO ₄ ^{3−}		[34]
				PO ₄ ^{3−}		[37]
				PO ₄ ^{3−}		[65]
				PO ₄ ^{3−}		[66]
				P		[4]
				P	PO ₄ ^{3−} -P (river water)	[11]
	Green-lipped mussels	<i>Perna canaliculus</i>			PO ₄ ^{3−} (greywater)	[67]
					NH ₄ ⁺ , PO ₄ ^{3−} (lake)	[68]
				PO ₄ ^{3−}		[69]
	Green-lipped mussels	<i>Perna canaliculus</i>		PO ₄ ^{3−}		[6]
	Green mussel shells	<i>Perna viridis</i>			NH ₃ -N (raw leachate)	[9]
	Green mussel shells	<i>Perna viridis</i>			NH ₃ -N (raw leachate)	[30]
	Green mussels	<i>Perna viridis</i>			NH ₃ -N (raw leachate)	[70]
	Green mussels	<i>Perna viridis</i>			NH ₃ -N (raw leachate)	[71]
					NH ₃ -N (raw leachate)	[72]
Oyster shells				P		[7]
				PO ₄ ^{3−}		[19]
				P		[28]
				PO ₄ ^{3−}		[29]
				P		[61]
				P		[73]
				P		[74]
				P		[75]
				PO ₄ ^{3−}		[76]
				PO ₄ ^{3−}		[77]
				P		[78]
				NH ₄ -N		[22]
					PO ₄ ^{3−} (lake water)	[38]
					NH ₃ , NO ₃ [−] , PO ₄ ^{3−} (landfill leachate)	[36]
					TP and TN (river water)	[40]
					TN (synthetic domestic wastewater)	[79]
					NH ₄ -N (simulated wastewater)	[80]
					NH ₃ ⁺ , NO ₃ [−] (recirculating aquaponic)	[81]
					P (treated swine wastewater from constructed wetlands)	[82]
			NH ₄ -N (domestic wastewater)			[83]
			NH ₃ -N/TN (effluent from primary wastewater settling tank)			[84]
			NO ₃ -N, NH ₄ -N, PO ₄ ^{3−} , and TP (domestic wastewater)			[85]
			NO ₃ -N and TP (secondary clarifier effluent)			[86]
			P (swine wastewater)	P		[87]
			NH ₃ ⁺ , TP (municipal)			[88]

Table 1. Cont.

CWS Type	Common (English) Name	Scientific (Latin) Name	Wastewater Type and Target Pollutant			Reference
			Domestic/Municipal Wastewater	Synthetic Wastewater	Other Wastewater	
Egg shells				NO ₃ -N and P	NO ₃ [−] (groundwater)	[10]
				NO ₃ [−]		[26]
				P		[27]
				NH ₄ ⁺		[35]
				P		[62]
				NO ₃ [−]		[89]
				P-PO ₄		[90]
				P-PO ₄		[91]
				P-PO ₄		[92]
				P		[93]
Bivalve shells			P (anaerobic digester effluent) P (dewatered anaerobic sludge) P (preliminary treatment b effluent and anaerobic digester supernatant)	P		[20]
				P		[54]
				P, PO ₄ ^{3−}		[55]
				P		[57]
Clam shells	European flat shells	<i>Anomalocardia brasiliiana, Tagelus plebeius</i>	TP, PO ₄ ^{3−} -P (anaerobically digested swine)	P		[58]
Clam shells		<i>Anomalocardia brasiliiana, Tagelus plebeius</i>		P		[56]
White hard clams		<i>Meretrix lusoria</i>		P		[5]
Crushed coral, oyster, and mussel-shells			PO ₄ ^{3−} -P (secondary effluent)	P		[94]
Marsh clam, mussel shells, and egg shells				PO ₄ ^{3−}		[95]
Snail and clam shells				PO ₄ ^{3−}		[31]
Zebra mussels			P (treated domestic wastewater)	P		

3.2. Wastewater Type and Form of Treated Nutrient

Calcareous waste shells have been investigated more for phosphorus removal (70% of studies) than for nitrogen (30%) (Figure 2c), possibly because phosphorus is easier to remove via adsorption, chemisorption, and precipitation compared to nitrogen. Phosphorus can be expressed as phosphate (PO₄^{3−}), phosphate–phosphorus (PO₄-P), elemental phosphorus (P), and total phosphorus (TP), while nitrogen can be stated as ammonia (NH₃⁺), ammonium (NH₄⁺), ammoniacal nitrogen (NH₃-N), nitrate (NO₃[−]), nitrate–nitrogen (NO₃-N), and total nitrogen (TN) (Table 1). Most authors used synthetic wastewater (Figure 2c) in their experiments to remove nutrients (P—68%, N—26%), followed by domestic/municipal wastewater (P—20%, N—26%). A few reasons may explain the predominance of using laboratory synthetic wastewater in these studies. Firstly, real wastewater is inherently variable and chemically complex [42], so using synthetic wastewater, especially in early-stage laboratory experiments, is simpler and helps reduce confounding experimental effects. Secondly, access to and the potential pathogenic risks of using real wastewater can impede the progress of investigations due to health and safety concerns and logistical complexity. Lastly, field experiments would likely use actual wastewater, require larger volumes, and would be influenced by prevailing climatic variables, so they have more logistical requirements. Most of these studies used small wastewater volumes (between 15 and 2000 mL) (Table S1, Supplementary Materials) and were bench-top-scale. They focussed on

the effects of different experimental parameters (e.g., dosage, HRT, and temperature) on nutrient removal [69,95] and identified the nutrient removal kinetics at play [76,93]. Of all the non-synthetic wastewaters, landfill leachate was used to investigate nitrogen (especially ammoniacal nitrogen) removal, possibly because landfill leachate is characteristically high in ammonia [30,36].

The different nutrient forms investigated, as a function of the different CWS types, are detailed in Table 1 and summarised in Figure 2d. Phosphorus (predominantly phosphate) removal was investigated using all eight CWS types, including a combination of shells, whereas nitrogen removal was only tested by three CWS types: oysters, mussels, and eggshells (Figure 2d). It is likely that a greater number of studies investigated phosphate removal because it is well reported how phosphate is removed by adsorption or chemisorption under calcareous conditions [7,60,91]. During adsorption, trivalent phosphate anions (PO_4^{3-}) bond more strongly with divalent calcium cations (Ca^{2+}) compared to monovalent nitrate anions (NO_3^-), resulting in faster and stronger phosphate removal [60].

The total nitrogen (TN) concentration was only measured in two studies (Figure 2d, Table 1), both using oyster shells in biological filter systems with aerobic nitrification in the upper layer(s) and anaerobic denitrification in the lower biofilter layers [79,84]. Conventional biological aerated biofilters (BAFs) did not remove TN, due to the absence of an anoxic stage [84]. However, raw oyster shells incorporated as alkaline filters were reported to maintain the anoxic system's neutral pH [22] and act as a biocarrier for denitrifiers [84]. The removal of other nitrogenous (ammonia and nitrate) forms was investigated using oyster shells (12 studies), mussel shells (7 studies), and eggshells (4 studies) (Figure 2d). In the absence of a microorganism-driven system, the chemisorption of ammonia occurred heterogeneously on multilayers of the shells [18]. In contrast, Daud et al. [72] and De-tho et al. [70], who investigated ammonia removal from landfill leachate, deduced that a composite adsorbent containing mussel shells provided an increased surface area for greater monolayer adsorption compared to mussel shells only (167 mg/g). This composite adsorbent achieved a 60% reduction and adsorption capacity of 200 mg/g of ammoniacal nitrogen. Bhatnagar and Sillanpää [41] found that surface area does not substantially influence nitrate adsorption but that positively charged surfaces do, presumably as this increases the binding of nitrate anions. They found better nitrate adsorption with adsorbent protonation (activated carbon, zeolites, industrial wastes), ionic exchange (clay-based adsorbents, double-layered hydroxides), and an increase in the presence of amine and hydroxyl functional groups (chitosan, agricultural waste materials).

Most studies reported the removal of a single nutrient, and less emphasis has been placed on the simultaneous removal of nitrogenous compounds and phosphate. As mentioned earlier in this section, phosphate removal is well documented compared to that of nitrogenous compounds. Nevertheless, the successful removal of both nutrients from domestic or municipal wastewater using biofiltration [85,88] and coagulation/flocculation [60] was reported. In general, CWSs in biofilters remove phosphate via chemical sorption and precipitation, while the removal of nitrate and ammonium is facilitated by bacteria during nitrification and denitrification processes [85]. On the other hand, when CWSs are used in coagulation/flocculation, its main constituent, calcium oxide (CaO), transforms into calcium hydroxide (CaOH) upon hydration, which simultaneously removes phosphate and nitrate via the precipitation of calcium phosphate (hydroxyapatite) and calcium nitrate-hydroxide complexes, respectively [60]. A more detailed explanation of both nutrient removal mechanisms can be found in Section 3.5.

3.3. Effects of Experimental Conditions on Nutrient Removal

Table S1 (Supplementary Materials) summarises the key experimental conditions and nutrient removal efficiencies across the studies. Experimental variables include CWS type, pollutant concentration and form, adsorbent dosage, hydraulic retention (contact) time, pH, and temperature.

The data are also shown as box plots, highlighting data ranges and trends across the studies (Figure 3). The initial pollutant concentration(s) (Figure 3a), CWS adsorbent dosage (Figure 3b), HRT (Figure 3c), and wastewater volume (Figure 3d) for all CWS types are compared. Abbreviations for each shell type are denoted as oyster shells (OSs), mussel shells (MSs), eggshells (ESs), clam shells (CSs), white hard clams (wCSs), bivalve shells (BSs), zebra mussels (ZSs), and combination of shells (CoS).

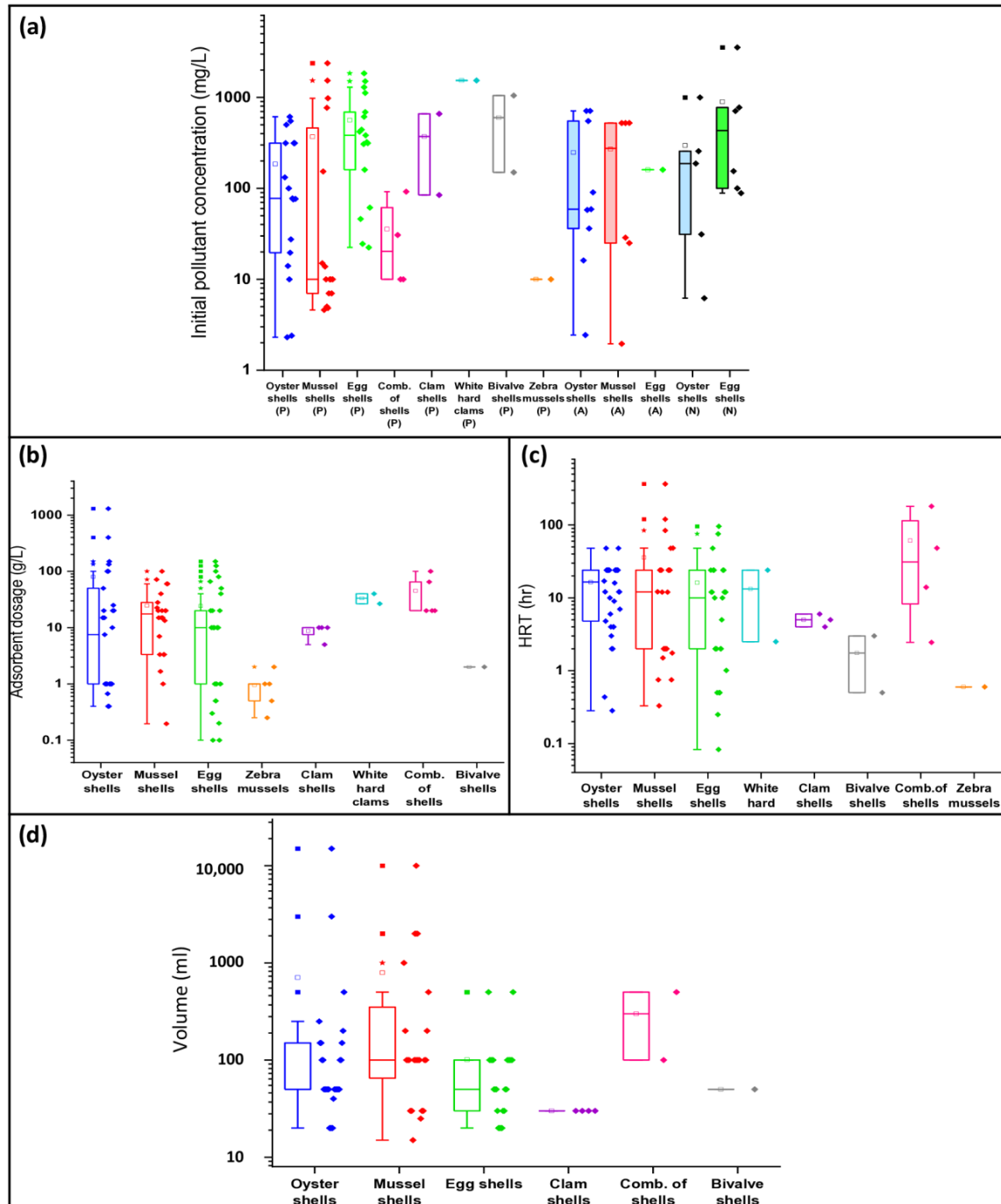


Figure 3. (a) Initial pollutant concentration (mg/L); (b) adsorbent dosage (g/L); (c) hydraulic retention time; HRT (hours); and (d) sample test volume (mL). Total sample number, $n = 155$ (a), $n = 91$ (b), $n = 70$ (c), and $n = 84$ (d). Legends: 25–75%, I range within 1.5IQR; — median line; □ mean; * outlier; ■ extreme values; Comb. of shells—combination of shells. Data points within boxplots are optimum values reported or mid-value if values are reported as ranges.

Figure 3a displays the initial pollution concentration of phosphate (P), ammonium (A), and nitrate (N) for different shell types. Generally, a larger nutrient concentration range (2–1500 mg/L) was observed for the main shell types studied (i.e., OS, MS, and ES). Phosphate removal in OS was tested between 2 and 600 mg/L with a median of 80 mg/L. In contrast, MS showed two distinct ranges, 5–20 mg/L (low) and 150–1000 mg/L (medium–high), with an overall 10 mg/L median. ES had a higher median of 400 mg/L, with more studies conducted at higher phosphate concentrations. Higher phosphate concentrations in synthetic wastewater compared to non-synthetic wastewater were used for all shell types to support isotherm and kinetic studies [8,36,91,92]. Conversely, when lower phosphate concentrations were used (in MS), they corresponded to phosphate concentrations typical in freshwaters (e.g., river or lake) (Table 1).

The median ammonium concentration tested in OS was 60 mg/L, while MS (median 300 mg/L) showed three distinct concentration ranges between 2 and 500 mg/L. The high ammonium concentration corresponded to synthetic wastewater, raw landfill leachate, and swine wastewater. The medium ammonium range (100 mg/L) occurred in synthetic and domestic wastewater, while the low ammonium level (<10 mg/L) was from lake water and aquaponic wastewater (Table 1). Very few studies were observed using OS and ES for nitrate removal, with none recorded for MS. The nitrate concentration tested for OS ranged from 6 to 300 mg/L with a median of 200 mg/L, while for ES, it ranged higher at 80–800 mg/L (median 400 mg/L). Like ammonium, a high initial nitrate concentration prevailed in synthetic wastewater, with a medium-strength nitrate concentration in domestic wastewater and a low nitrate concentration in aquaponic wastewater and treated effluent.

Figure 3b shows the range of adsorbent dosages (in g/L) for different shell types. A larger range of adsorbent dosages was found in studies using OS, MS, and ES (0.1–100 g/L), a reflection of the greater number of studies using these shell types. While their medians are relatively close (10–20 g/L), the mean for OS (90 g/L) was higher than those of MS and ES (both at 25 g/L), suggesting that OS has a wider application in water treatment (represented by an extended distribution plot). Oyster shells dominated as a CWS adsorbent compared with other shell types. This may be because of their wider availability, higher calcium content, and higher resulting alkalinity. As stated earlier, the CaCO_3 content in oysters, mussels, and eggshells ranges from 90 to 97%. Interestingly, the mineral composition of shells from the same species but collected from different places also differed [15], which might be attributed to variations in shells' nutrition and age and the habitat's temperature, salinity, and pH [96]. Furthermore, differences in pyrolysis conditions likely affect the dosages used in the experimental studies. For example, CWSs produced by slow calcination have a higher BET surface area (81 m^2/g) than when produced by fast calcination (20 m^2/g) [46].

Other shell types, such as Zebra mussels, clams, white hard clams, bivalves, and combined shells, were studied in a narrower adsorbent dosage range, a reflection of the fewer publications and possibly shell regional availability. For example, abundant bivalve shells in the freshwater lake of Tonle Sap, Cambodia, were used as adsorbents for phosphate removal to control eutrophication [55], and white hard clam waste shells were utilised to remove phosphorus from anaerobically digested swine wastewater in Vietnam [56]. Zebra mussels, an invasive species in North America, were mined for calcium carbonate to remove phosphorus from domestic wastewater [31].

The influence of hydraulic retention time (HRT), or the time the CWS adsorbent was in contact with the wastewater, on each shell type is shown in Figure 3c. Most shell types were investigated within an HRT range of 0.083–50 h. Median values for all shell types ranged from 10 to 20 h, except for combined shells, which had a higher median of 30 h. The two highest data points in the CoS studies corresponded to an unusually long contact time of 4 and 15 days in batch adsorption assays that skewed this median [5,94].

The wastewater volume used in the experiments is shown in Figure 3d. OS and MS sample volumes ranged between 20 and 600 mL, with median values ranging between 50 and 100 mL (like ES), suggesting that most laboratory experiments considered 50–100 mL

sufficient to investigate the effect of CWM on nutrient removal under laboratory conditions. The exception was a study that reported combined shells with a median of 300 mL used in the experiments. Field trials using CWS-derived media to treat nutrients would require much greater volumes of wastewater (synthetic or real) and provide valuable additional datasets to understand the effects of wastewater volume on nutrient removal.

3.4. Isotherms and Kinetics

For the practical application of adsorption processes to treat pollutants, it is crucial to have data related to equilibrium, the adsorbent's adsorption capacity, and the kinetics of the process [97]. Adsorption kinetics provide important data for designing, optimising, and troubleshooting treatment systems relying on adsorption. Adsorption isotherms explain the adsorption/desorption mechanisms of particular treatment processes [66]. Table S2 (Supplementary Materials) summarises the removal mechanisms, isotherms, and reaction kinetics reported in the experimental studies reviewed. Figure 4 shows the CWS type, and the isotherm and kinetic models reported.

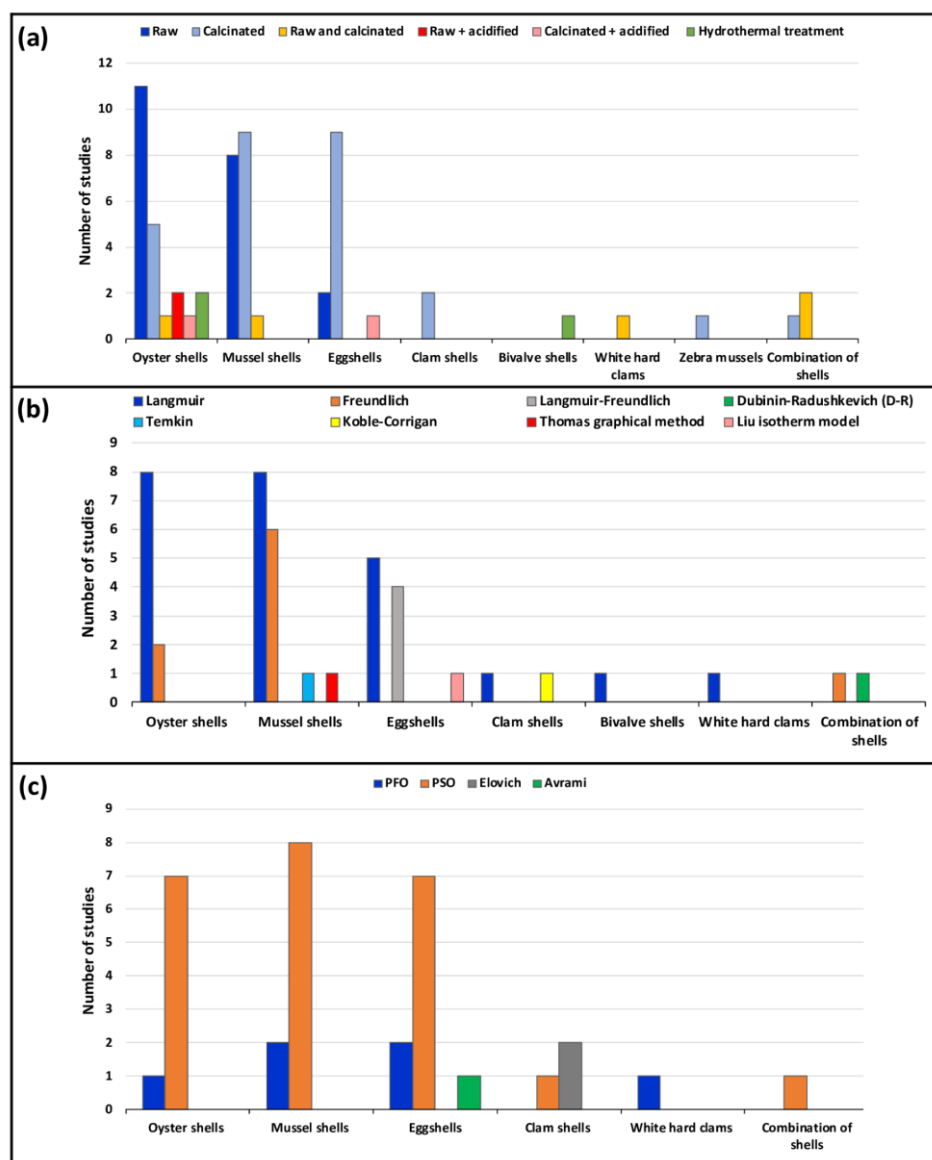


Figure 4. (a) Type and condition of the shell used for treatment ($n = 60$ studies), (b) isotherm models applied per shell category ($n = 42$), and (c) kinetic models per shell type ($n = 33$). PFO—pseudo-first order; PSO—pseudo-second order.

Raw (untreated) CWS adsorbents have a lower specific surface area and porosity [19] and, hence, a lower pollutant removal potential compared to CWSs modified by calcination, acidification, or hydrothermal treatment. For instance, the specific surface area measured by Brunauer–Emmett–Teller (BET) analysis on raw oysters ($4.05 \text{ m}^2/\text{g}$) [98], mussels ($0.055 \text{ m}^2/\text{g}$) [99], and eggshells ($0.30 \text{ m}^2/\text{g}$) [54] increased to $64.6 \text{ m}^2/\text{g}$ [100], $1.22 \text{ m}^2/\text{g}$ [6], and $2.8 \text{ m}^2/\text{g}$ [54], respectively, after calcination.

Calcination causes volatilisation of the organic components, increasing the calcareous shell's specific surface area and porosity [19,33]. Heating the shell to above 500°C converts CaCO_3 to CO_2 and calcium [28] and changes the crystal structure of CaCO_3 [6]. In this stage, the orthorhombic crystal structure—or aragonite, the main form of calcium carbonate in CWSs—is transformed into a calcite polymorph with a trigonal rhombohedral structure [4,6,101]. Calcination is the most widely used method to enhance CWS capacity to remove nutrients from wastewater (Figure 4a). Most papers reporting calcination or other CWS modification used oyster shells, reflecting the dominance of OS in the experimental studies.

CWS acidification is applied by immersing the shells in a low-concentration acid solution overnight to dissolve CaCO_3 , thus producing CaO [89]. The hydrothermal method involves crystallising minerals from high-temperature aqueous solutions in an autoclave or a microwave under high vapour pressures [102]. Lai [78] processed oyster shells by sintering with silica micro-powder using high-temperature and observed that hydrothermal treatment showed a large adsorptive phosphorus capacity and long 'service life'. The sintering and hydrothermal treatment result in the partial transformation of CaCO_3 into CaO , which partly reacts with SiO_2 (silicon dioxide) to produce CaSiO_3 (calcium silicate), resulting in activated Ca^{2+} which reacts with phosphate in wastewater to form calcium phosphate precipitates [76,78].

Isotherm models reported in the CWS studies are shown in Figure 4b. Common models (in descending order of frequency) are Langmuir, Freundlich, and Langmuir–Freundlich. The Langmuir and Freundlich models are the two most common adsorption isotherm models to describe adsorbate removal processes and mechanisms [76]. While the Langmuir isotherm model involves adsorbate interaction on completely homogenous surfaces with the same activation energy, the Freundlich isotherm model is suitable for highly heterogeneous surfaces [34,76]. The Langmuir–Freundlich, or Sips, isotherm assumes the surface is homogeneous, but the adsorption is a cooperative process due to sorbate–sorbate interactions. This model acts like the Langmuir model (monolayer adsorption) at a high adsorbate concentration, while it behaves like the Freundlich model at a low adsorbate concentration [92,103]. Other relevant isotherm models reported in the CWS adsorption studies are Temkin [69], Dubinin–Radushkevich (D-R) [95], and Koble–Corrigan [58].

It was found that two-thirds of the reviewed studies involved isotherm investigation. Langmuir is the most common isotherm in studies involving oyster shells, mussel shells, and eggshells, indicating that adsorption occurs by monolayer deposition at the surface, with each site only allowing one adsorbate unit. The Freundlich isotherm was more commonly reported in studies with mussel shells, which suggests multilayer adsorption on non-uniform surfaces on this type of shell [103]. It is postulated that active sites on the mussel shells' surface strongly bind with the first layer of the adsorbate (e.g., phosphate), and that the binding strength decreases with increasing adsorbate layers. Furthermore, oyster shells are mostly used in raw form (Figure 4); for this, the Langmuir isotherm seems to produce the best fit. In the case of mussel shells, they are mainly calcinated, and the Freundlich model seems to work best. Interestingly, a Langmuir–Freundlich isotherm is only observed for eggshell studies, implying that monolayer and multilayer adsorption occur simultaneously.

Of all 64 reviewed studies, only half reported process kinetics data (Figure 4c). Of these, most (73%) reported the pseudo-second-order (PSO) model to explain the experimental data better than the pseudo-first-order (PFO) (18%), Elovich (6%), or Avrami (3%) models. Nutrient removal by the three main shell types (i.e., oyster, mussel, and eggshells)

followed PSO rather than PFO kinetics. The PFO model generally fits the data well over the first 20–30 min of the adsorption process, while the PSO model describes well the adsorption behaviour over the whole time range [103]. Hence, it is unsurprising to note a high agreement between the PSO model and the Langmuir isotherm [7,65,103]. The PSO kinetic model assumes that the adsorbate removal process is controlled by chemisorption with predominant monolayer adsorption [7,20]. In contrast, the PFO model assumes that the adsorption rate is determined by physical interaction with a one-on-one adsorption mechanism in which one pollutant unit is adsorbed onto one adsorbent surface site [8]. The Elovich kinetic model is only observed for clam shells, suggesting adsorption on very heterogeneous shell surfaces [58] and possible chemical reactions on the surface of the shells (adsorbent) [57].

3.5. Removal Mechanisms

Raw CWSs are mainly made of CaCO_3 aragonite [6,60], which is less effective as an adsorbent for phosphate removal. Upon calcination at 500–600 °C, CaCO_3 aragonite converts to calcium carbonate calcite (also known as calcite) [4,6,60], and further calcination at 800 °C produces CaO, the most effective form for phosphate precipitation [25,33,38]. It is reported that when using CWSs, phosphate is removed by retention on calcite rather than on aragonite [4] via adsorption and the nucleation of calcium phosphate (hydroxyapatite) precipitate [6]. Adsorption removal on calcite occurs on the particles' surface [4], creating sites for the initial binding between calcium and phosphate [69] and subsequently initiating the heterogeneous nucleation of calcium phosphate precipitates on calcite surfaces [6]. With time, more precipitates are formed by the reaction of hydrated CaO or CaOH with phosphate [60], thus enhancing phosphate removal through a precipitation mechanism [4]. It was found that precipitation can remove phosphate in larger stoichiometric amounts than adsorption [4].

In line with the above, Abeynaïke et al. [6] reported that a 95% or higher phosphate removal was achieved with partially calcinated mussel shells (calcite) compared to 22–45% with raw mussel shells. A similar result was also obtained by Daudzai et al. [60], where 85% phosphate removal and no nitrate removal were recorded for unrinsed raw seashells. In contrast, unrinsed calcinated seashells were able to remove almost 100% of phosphate and nitrate.

Nitrogenous compounds, such as ammonium (NH_4^+) and nitrate (NO_3^-), are removed via chemisorption [18,35,36] or physisorption [10]. Monovalent nitrate anions (NO_3^-) are known to bond weakly with divalent calcium cations (Ca^{2+}) compared to trivalent phosphate anions (PO_4^{3-}) [60]. In addition, their high solubility makes them difficult to remove. However, the presence of O–Ca–O functional groups and CO_3^{2-} ions in calcinated mussel shells facilitate nitrate removal by the formation of calcium nitrate–hydroxide complexes [60], as shown in Figure 5. Ammonium removal via chemisorption reactions such as ion exchange and electrostatic attraction occurs heterogeneously on multilayers of raw mussel shells, with two dominant functional groups, C–O and C=O, playing the main role [18]. While the higher presence of the C–O functional group and inorganic CO_3^{2-} in calcinated eggshells improves ammonium adsorption, the specific surface area did not significantly influence ammonium adsorption [35].

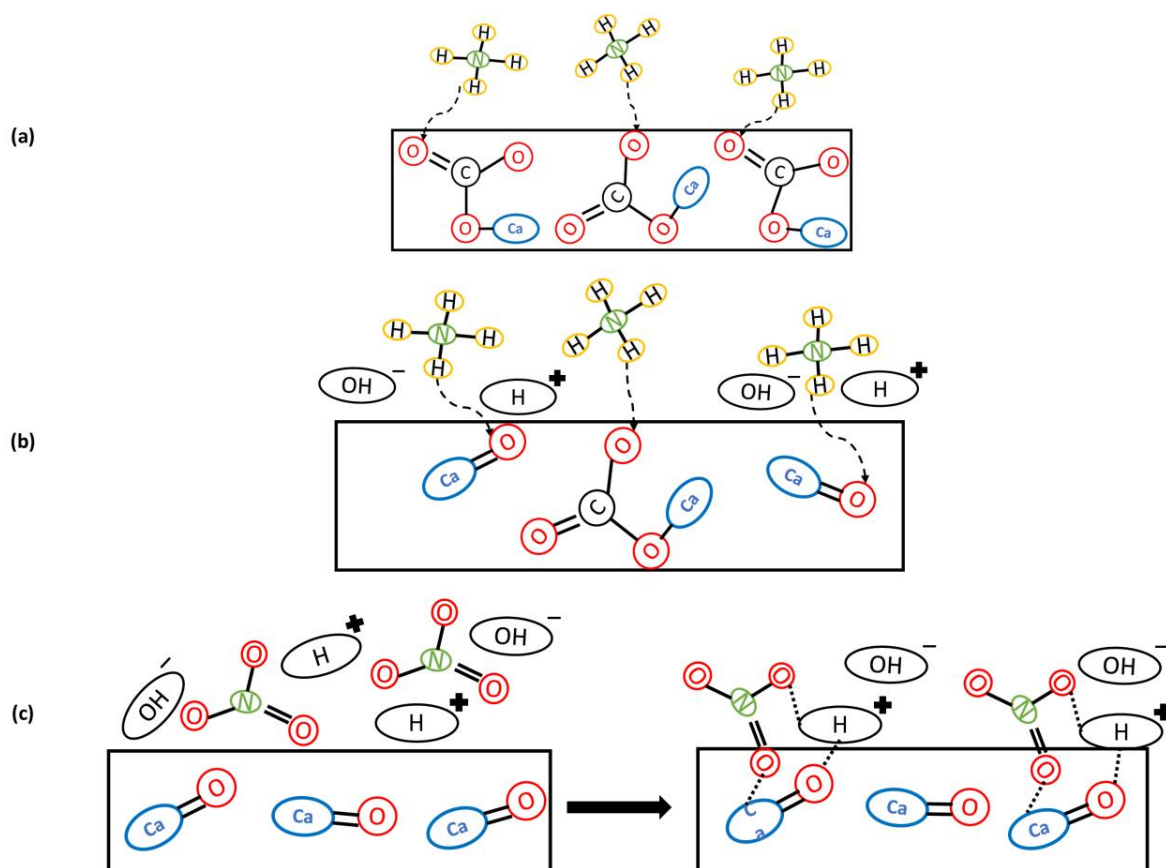


Figure 5. Removal mechanisms of ammonium in (a) raw shells, (b) calcinated shells, and (c) nitrate in calcinated shells.

3.6. Effects of Experimental Variables on Nutrient Removal

The effect of CWS adsorbent particle size (Figure 6), adsorbent dosage (Figure 7a), and hydraulic retention time (Figure 7b) on nutrient removal was further investigated in the form of scatter plots and correlation analyses. Nutrient removal showed no clear correlation with CMS adsorbent particle size (Figure 6a (phosphate) and Figure 6b (nitrate and ammonium)), probably due to the large variation in experimental conditions used across the different studies. These variables, such as different wastewater types, pollutant strength, raw or modified CWSs, and operational conditions (pH, temperature), likely affect the adsorption capacity regardless of the particle size. More data were available for phosphate than nitrogen compounds to draw any potential relationships. Oyster shells had a larger particle size range with strong adsorption capacity (up to 1000 mg/g) across this range (Figure 6a), suggesting that they are an effective adsorbent for phosphate removal from wastewater [39]. In contrast, eggshells exhibited similar adsorption capabilities as oyster shells but were only tested with particle sizes of <1 mm. Mussel shells were tested within a much smaller particle size range (around 1 mm) but showed very large variations in adsorption capacity.

The relationship between pollutant removal efficiency and adsorbent dosage across the studies is shown in Figure 7a,b (insufficient data were reported for nitrate to include). The only CWS type that showed a relationship between adsorbent dosage and treatment efficiency was oyster shells ($n = 4$) treating ammonium at a relatively high adsorbent dosage (Pearson's r : 0.9249, $R^2 = 0.8555$). Nonetheless, eggshells consistently removed >80% phosphate, with both oyster and mussel shells' phosphate removal being more variable (between 20 and 100%) (Figure 7b). One important variable to note is that most of the oyster shell studies used synthetic wastewater compared to the mussel shell studies, which may help explain the greater MS treatment variability.

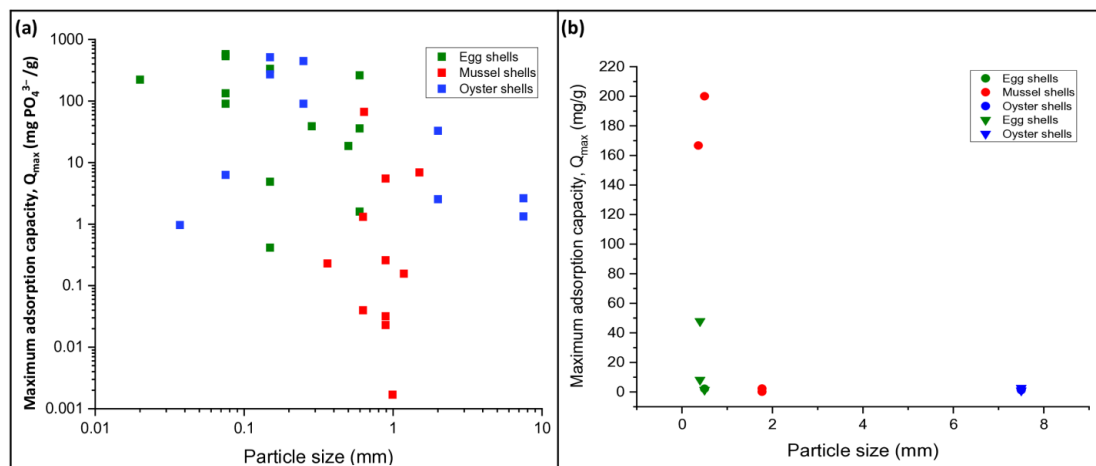


Figure 6. (a) PO_4^{3-} and (b) NH_4^+ and NO_3^- adsorption capacity as a function of particle size (mm) for egg, mussel, and oyster shells. Legend: ● ammonium and ▼ nitrate. Data points in the graph represent the mid-value of the particle size range. Note: (a) eggshells ($n = 13$), mussel shells ($n = 11$), and oyster shells ($n = 10$); (b) eggshells (NH_4^+) ($n = 1$), mussel shells (NH_4^+) ($n = 4$), oyster shells (NH_4^+) ($n = 2$), eggshells (NO_3^-) ($n = 3$), and oyster shells (NO_3^-) ($n = 2$).

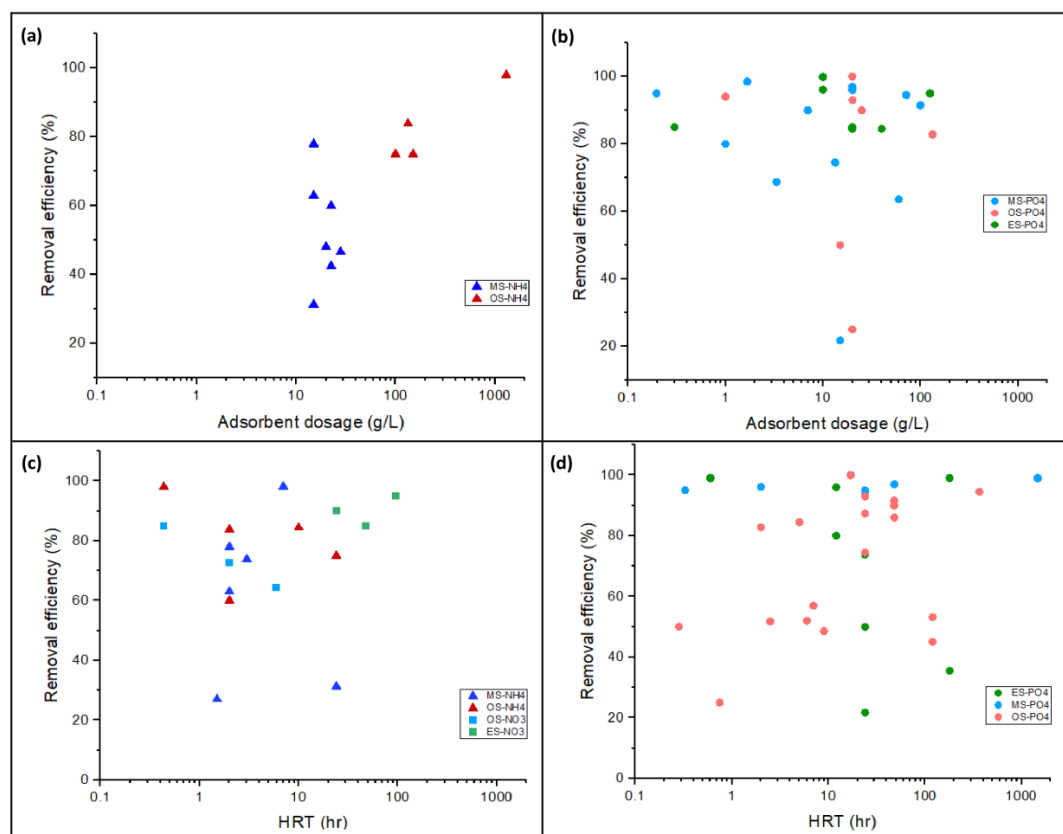


Figure 7. Relationship between pollutant removal efficiency and adsorbent dosage for (a) NH_4^+ and (b) PO_4^{3-} , and hydraulic retention time (HRT) for (c) NH_4^+ and NO_3^- , and (d) PO_4^{3-} . For values in a range, the mid-value is used and represented as data points. Note: (a) mussel shells (NH_4^+) ($n = 7$) and oyster shells (NH_4^+) ($n = 4$); (b) mussel shells (PO_4^{3-}) ($n = 12$), oyster shells (PO_4^{3-}) ($n = 8$), and eggshells (PO_4^{3-}) ($n = 7$), (c) mussel shells (NH_4^+) ($n = 7$), oyster shells (NH_4^+) ($n = 5$), oyster shells (NO_3^-) ($n = 4$), and eggshells (NO_3^-) ($n = 3$); and (d) eggshells (PO_4^{3-}) ($n = 8$), mussel shells (PO_4^{3-}) ($n = 7$), and oyster shells (PO_4^{3-}) ($n = 19$). Not shown in the graph is an outlier for oyster shells (NO_3^-) (-229% , 9.6 h).

The relationship between nutrient removal and HRT is shown in Figure 7c,d. There were insufficient (or absent) data reported in the reviewed studies to comment on the performance of some CSW–nutrient combinations (e.g., ammonium removal by eggshells and nitrate removal with oyster and mussel shells). The only CWS types that showed apparent relationships between the parameters were oyster shells treating nitrate (Pearson's r : -0.9374 , $R^2 = 0.8787$) and mussel shells treating phosphate (Pearson's r : 0.8047 , $R^2 = 0.6476$), revealing that a higher nitrate removal is achieved with a lower HRT for oyster shells, and a consistently high phosphate removal at $>90\%$ for mussel shells regardless of the HRT (indicative of a fast and relatively stable reaction) (Figure 7d).

3.7. Possible Reuse of Post-Treatment Adsorbents

A few studies reviewed in this manuscript discussed nutrient desorption, particularly phosphate, after wastewater treatment [60,69,104]. Desorption would allow for nutrient recovery and reuse and would help expand the lifespan of the adsorbents as they are reused [69]. The desorption of phosphate was performed using 2% citric acid for an hour with more than an 80% successful regeneration rate [69]. Daudzai et al. [60] reported the use of 0.5 M HCl at a 1% dosage, achieving 80% and 98% successful regeneration for phosphate and nitrate, respectively. Coincidentally, both chemicals (2% citric acid and 0.5 M HCl) were applied as desorption agents with a high regeneration rate above 90% [104]. The full desorption of phosphate occurred with 2% citric acid and 0.5 M HCl, suggesting that the adsorbed phosphate would be bioavailable to plants if the CWS adsorbent was to be used as a soil conditioner for agriculture [104]. Pap et al. [104] also suggested that post-treated CWS adsorbent could be potentially applied as a soil amendment in acidic soils with limited phosphate-adsorbing capacity. Another possible reuse of spent CWSs would be as construction material, e.g., a replacement for magnesium phosphate cement [48].

4. Conclusions

This systematic review on nutrient removal from wastewater by calcareous waste shells (CWSs) revealed that most studies were conducted in the laboratory using synthetic wastewater and small (50–100 mL) wastewater volumes. Studies have focussed more on phosphorus removal than on nitrogen. Much higher phosphate removal levels have been reported compared to any nitrogenous compound. It also revealed that calcination is the most frequently used method to enhance nutrient adsorption capacity. In terms of sorption models, the Langmuir isotherm fits experimental data with raw oyster shells best, while the Freundlich model fits data better from calcinated mussel shells' experiments. Furthermore, a higher agreement has been reported between experimental data and the pseudo-second-order kinetic model (73%) than the pseudo-first-order model (18%) for all shell types. An examination of the effect of individual experimental variables on nutrient removal was inconclusive, mainly due to the limited number of individual data points reported coupled with the confounding effects of multiple different experimental variables across the studies. Identifying and controlling for confounding variables are crucial in establishing reliable correlations and drawing meaningful conclusions from research findings. The application of laboratory results to real-world solutions requires certainty on the effects of critical individual variables such as HRT, temperature, and wastewater strength. While there is commendable laboratory research showcasing the valorisation of CMS in wastewater treatment, this needs to be translated into larger-scale trials to provide more certainty in sustainable design solutions and a pathway for scaling with certainty in effectiveness.

Several potential research questions arise that can be explored in future studies:

1. Does the CaCO_3 content of different CWSs affect nutrient removal?
2. Which experimental variable (HRT, adsorption dosage, particle size, or wastewater strength) is most influential on nutrient removal capacity?
3. To what extent would climatic variables influence the adsorption capacity of CWS removing nutrients if experiments were performed under field conditions?

4. Would the isotherms and kinetic studies change if studies were conducted for longer under field conditions?
5. Can CWSs be modified (functionalised) differently to improve nitrate adsorption?

Supplementary Materials: The following supporting information can be downloaded at <https://www.mdpi.com/article/10.3390/environments11060119/s1>. Table S1: Experimental conditions and removal efficiencies using CWS; Table S2: Isotherm and kinetic results of studies that used CWS for treating nutrients in water.

Author Contributions: Conceptualisation, K.T.W., R.B.-M. and A.D.O.; literature review, K.T.W., R.B.-M. and A.D.O.; data curation, K.T.W., R.B.-M. and A.D.O.; writing—original draft preparation, K.T.W.; writing—review and editing, R.B.-M. and A.D.O. All authors have read and agreed to the published version of the manuscript.

Funding: This work was supported by the Science for Technological Innovation (SfTI) National Science Challenges (NSC) Spearhead 9—Clean Water Technology (CWT) project (contract No. 2020-S9-CRS).

Data Availability Statement: No new data were created or analyzed in this study. Data sharing is not applicable to this article.

Conflicts of Interest: The authors declare no conflicts of interest.

References

1. Rauh, E.; Hughes, S. Collaboration for source water protection in the United States: Community water systems engagement in nitrate pollution reduction. *WIREs Water* **2023**, *11*, e1682. [\[CrossRef\]](#)
2. Larned, S.; Booker, D.; Dudley, B.; Moores, J.M.R.; Baillie, B.; Schallenberg, M.; Moriarty, E.; Zeldis, J.; Short, K. *Land-Use Impacts on Freshwater and Marine Environments in New Zealand*; National Institute of Water & Atmospheric Research Ltd. (NIWA): Christchurch, New Zealand, 2018; p. 291. Available online: <https://environment.govt.nz/assets/Publications/Files/land-use-impacts-on-freshwater-and-marine-environments-.pdf> (accessed on 22 October 2023).
3. Reddy, K.R.; Dastgheibi, S.; Cameselle, C. Mixed versus layered multi-media filter for simultaneous removal of nutrients and heavy metals from urban stormwater runoff. *Environ. Sci. Pollut. Res.* **2021**, *28*, 7574–7585. [\[CrossRef\]](#)
4. Paradelo, R.; Conde-Cid, M.; Cutillas-Barreiro, L.; Arias-Estévez, M.; Nóvoa-Muñoz, J.; Álvarez-Rodríguez, E.; Fernández-Sanjurjo, M.; Núñez-Delgado, A. Phosphorus removal from wastewater using mussel shell: Investigation on retention mechanisms. *Ecol. Eng.* **2016**, *97*, 558–566. [\[CrossRef\]](#)
5. Zapater-Pereyra, M.; Mallocci, E.; van Bruggen, J.; Lens, P. Use of marine and engineered materials for the removal of phosphorus from secondary effluent. *Ecol. Eng.* **2014**, *73*, 635–642. [\[CrossRef\]](#)
6. Abeynaike, A.; Wang, L.; Jones, M.I.; Patterson, D.A. Pyrolysed powdered mussel shells for eutrophication control: Effect of particle size and powder concentration on the mechanism and extent of phosphate removal. *Asia-Pac. J. Chem. Eng.* **2011**, *6*, 231–243. [\[CrossRef\]](#)
7. Xu, Y.; Liao, H.; Zhang, J.; Lu, H.; He, X.; Zhang, Y.; Wu, Z.; Wang, H.; Lu, M. A Novel Ca-Modified Biochar for Efficient Recovery of Phosphorus from Aqueous Solution and Its Application as a Phosphorus Biofertilizer. *Nanomaterials* **2022**, *12*, 2755. [\[CrossRef\]](#)
8. Lee, J.-I.; Oh, J.-S.; Yoo, S.-C.; Jho, E.H.; Lee, C.-G.; Park, S.-J. Removal of phosphorus from water using calcium-rich organic waste and its potential as a fertilizer for rice growth. *J. Environ. Chem. Eng.* **2022**, *10*, 107367. [\[CrossRef\]](#)
9. Jones, M.I.; Wang, L.Y.; Abeynaike, A.; Patterson, D.A. Utilisation of waste material for environmental applications: Calcination of mussel shells for waste water treatment. *Adv. Appl. Ceram.* **2011**, *110*, 280–286. [\[CrossRef\]](#)
10. Zhou, L.; Xu, D.; Li, Y.; Pan, Q.; Wang, J.; Xue, L.; Howard, A. Phosphorus and Nitrogen Adsorption Capacities of Biochars Derived from Feedstocks at Different Pyrolysis Temperatures. *Water* **2019**, *11*, 1559. [\[CrossRef\]](#)
11. Yin, H.; Liu, L.; Lv, M.; Feng, L.; Zhou, J. Metal-Modified Mussel Shell for Efficient Binding of Phosphorus in Eutrophic Waters. *Int. J. Environ. Res.* **2020**, *14*, 135–143. [\[CrossRef\]](#)
12. Yousefi, H.; Douna, B.K. Risk of Nitrate Residues in Food Products and Drinking Water. *Asian Pac. J. Environ. Cancer* **2023**, *6*, 69–79. [\[CrossRef\]](#)
13. USEPA. *Aquatic Life Ambient Water Quality Criteria for Ammonia—Freshwater* (2013); USEPA: Washington, DC, USA, August 2013; p. 3. Available online: https://www.epa.gov/sites/default/files/2015-08/documents/fact_sheet_aquatic-life-ambient-water-quality-criteria-for-ammonia-freshwater-2013.pdf (accessed on 27 September 2023).
14. Keshvardoostchokami, M.; Majidi, M.; Zamani, A.; Liu, B. A review on the use of chitosan and chitosan derivatives as the bio-adsorbents for the water treatment: Removal of nitrogen-containing pollutants. *Carbohydr. Polym.* **2021**, *273*, 118625. [\[CrossRef\]](#)
15. Zhan, J.; Lu, J.; Wang, D. Review of shell waste reutilization to promote sustainable shellfish aquaculture. *Rev. Aquac.* **2022**, *14*, 477–488. [\[CrossRef\]](#)

16. Heasman, K.G.; Scott, N.; Ericson, J.A.; Taylor, D.I.; Buck, B.H. Extending New Zealand's Marine Shellfish Aquaculture Into Exposed Environments—Adapting to Modern Anthropogenic Challenges. *Front. Mar. Sci.* **2020**, *7*, 565686. [\[CrossRef\]](#)
17. MPI. Grinding Mussel Shells into Calcium Carbonate Offers High-Value Waste Solution. 7 February 2023. Available online: <https://www.mpi.govt.nz/news/media-releases/grinding-mussel-shells-into-calcium-carbonate-offers-high-value-waste-solution/#:~:text=%22Currently%20New%20Zealand%20mussel%20shells,biowaste,%22%20says%20Dr%20Gobindlal> (accessed on 10 August 2023).
18. Nguyen, V.Q.; Van, H.T.; Le Sy, H.; Nguyen, T.M.L.; Nguyen, D.K. Application of Mussel-derived biosorbent to remove NH_4^+ from aqueous solution: Equilibrium and Kinetics. *SN Appl. Sci.* **2021**, *3*, 496. [\[CrossRef\]](#)
19. Tran, T.-T.; Tran, N.-N.T.; Sugiyama, S.; Liu, J.-C. Enhanced phosphate removal by thermally pretreated waste oyster shells. *J. Mater. Cycles Waste Manag.* **2021**, *23*, 177–185. [\[CrossRef\]](#)
20. Panagiotou, E.; Kafa, N.; Koutsokeras, L.; Kouis, P.; Nikolaou, P.; Constantinides, G.; Vyrides, I. Turning calcined waste egg shells and wastewater to Brushite: Phosphorus adsorption from aqua media and anaerobic sludge leach water. *J. Clean. Prod.* **2018**, *178*, 419–428. [\[CrossRef\]](#)
21. Hart, A. Mini-review of waste shell-derived materials' applications. *Waste Manag. Res. J. A Sustain. Circ. Econ.* **2020**, *38*, 514–527. [\[CrossRef\]](#)
22. Li, C.; Lin, X.; Duan, L.; Liu, D.; Han, Z. Ammonia nitrogen removal in a biological nitrifying system using oyster shells as alkalinity-releasing filling materials. In Proceedings of the 2016 ASABE Annual International Meeting, Orlando, FL, USA, 17–20 July 2016. [\[CrossRef\]](#)
23. Onoda, H.; Kawade, H.; Takenaka, A. Preparation of calcium phosphates from artificial phosphorus wastewater and sea urchin shells. *J. Ecotechnology Res.* **2010**, *15*, 107–111. [\[CrossRef\]](#)
24. Anand, M.; Rangesh, K.; Maruthupandy, M.; Jayanthi, G.; Rajeswari, B.; Priya, R.J. Effect of CO_2 driven ocean acidification on calcification, physiology and ovarian cells of tropical sea urchin *Salmacis virgulata*—A microcosm approach. *Heliyon* **2021**, *7*, e05970. [\[CrossRef\]](#)
25. Lee, M.; Tsai, W.-S.; Chen, S.-T. Reusing shell waste as a soil conditioner alternative? A comparative study of eggshell and oyster shell using a life cycle assessment approach. *J. Clean. Prod.* **2020**, *265*, 121845. [\[CrossRef\]](#)
26. Jendia, A.H.; Hamzah, S.; Abuhabib, A.A.; El-Ashgar, N.M. Removal of nitrate from groundwater by eggshell biowaste. *Water Supply* **2020**, *20*, 2514–2529. [\[CrossRef\]](#)
27. Quispeima, A.; Pérez, S.; Flórez, E.; Acelas, N. Valorization of potato peels and eggshells wastes: Ca-biocomposite to remove and recover phosphorus from domestic wastewater. *Bioresour. Technol.* **2022**, *343*, 126106. [\[CrossRef\]](#)
28. Ohno, M.; Kobayashi, Y.; Sohma, R.; Suzuki, M.; Kose, T.; Asada, T.; Kawata, K. Examination and Evaluation of Oyster Shell Utilization with Rice Husk Biochar for Phosphorus Adsorption. *J. Water Environ. Technol.* **2022**, *20*, 71–83. [\[CrossRef\]](#)
29. Qiu, S.; Zhao, D.; Feng, Y.; Li, M.; Liang, X.; Zhang, L.; Luo, Y.; Zhang, K.; Wang, F. Adsorption performance and mechanism of Ca–Al-LDHs prepared by oyster shell and pop can for phosphate from aqueous solutions. *J. Environ. Manag.* **2022**, *303*, 114235. [\[CrossRef\]](#)
30. Detho, A.; Daud, Z.; Almohana, A.I.; Almojil, S.F.; Alali, A.; Din, M.F.M.; Rosli, M.A.; Memon, A.A.; Awang, H.; Ridzuan, M.B. Adsorption of chemical oxygen demand and ammoniacal nitrogen removal from leachate using seafood waste (green mussel shell) as low-cost adsorbent. *Desalination Water Treat.* **2022**, *260*, 102–110. [\[CrossRef\]](#)
31. McCorquodale-Bauer, K.; Cicek, N. Zebra mussel shells as an alternative mineral resource for lime production as a phosphorus precipitant. *Environ. Technol.* **2022**, *43*, 1446–1457. [\[CrossRef\]](#)
32. Amarowicz, R.; Synowiecki, J.; Shahidi, F. Chemical composition of shells from red (*Strongylocentrotus franciscanus*) and green (*Strongylocentrotus droebachiensis*) sea urchin. *Food Chem.* **2012**, *133*, 822–826. [\[CrossRef\]](#)
33. Morris, J.P.; Thierry, B.; Gauthier, C. Shells from aquaculture: A valuable biomaterial, not a nuisance waste product. *Rev. Aquac.* **2019**, *11*, 42–57. [\[CrossRef\]](#)
34. Salim, N.A.A.; Fulazzaky, M.A.; Puteh, M.H.; Khamidun, M.H.; Yusoff, A.R.M.; Abdullah, N.H.; Ahmad, N.; Lazim, Z.M.; Nuid, M. Adsorption of Phosphate from Aqueous Solution onto Iron-coated Waste Mussel Shell: Physicochemical Characteristics, Kinetic, and Isotherm Studies. *Biointerface Res. Appl. Chem.* **2021**, *11*, 12831–12842. [\[CrossRef\]](#)
35. Xu, D.; Cao, J.; Li, Y.; Howard, A.; Yu, K. Effect of pyrolysis temperature on characteristics of biochars derived from different feedstocks: A case study on ammonium adsorption capacity. *Waste Manag.* **2019**, *87*, 652–660. [\[CrossRef\]](#)
36. Morris, S.; Garcia-Cabellos, G.; Ryan, D.; Enright, D.; Enright, A.-M. Low-cost physicochemical treatment for removal of ammonia, phosphate and nitrate contaminants from landfill leachate. *J. Environ. Sci. Health Part A* **2019**, *54*, 1233–1244. [\[CrossRef\]](#)
37. Abdullah, N.H.; Liom, S.L.; Zainudin, A.H.; Huzil, M.A.I.; Yaacob, M.S.S.; Salim, N.A.A.; Kaamin, M.; Talaiekhazani, A. Waste Mussel Shells as an Adsorbent for Phosphate Removal in Solution: Kinetic and Isotherm Model. *Int. J. Nanoelectron. Mater.* **2022**, *15*, 25–36. Available online: <https://www.scopus.com/inward/record.uri?eid=2-s2.0-85129915856&partnerID=40&md5=136177ce9516a540537543ec95eaabeb> (accessed on 30 January 2023).
38. Huh, J.-H.; Choi, Y.-H.; Lee, H.-J.; Choi, W.J.; Ramakrishna, C.; Lee, H.-W.; Lee, S.-H.; Ahn, J.-W. The Use of Oyster Shell Powders for Water Quality Improvement of Lakes by Algal Blooms Removal. *J. Korean Ceram. Soc.* **2016**, *53*, 1–6. [\[CrossRef\]](#)
39. Popović, N.T.; Lorencin, V.; Strunjak-Perović, I.; Čož-Rakovac, R. Shell Waste Management and Utilization: Mitigating Organic Pollution and Enhancing Sustainability. *Appl. Sci.* **2023**, *13*, 623. [\[CrossRef\]](#)

40. Nam, G.; Choi, Y.-H.; Lee, N.; Ahn, J.W. Effect by Alkaline Flocculation of Algae and Phosphorous from Water Using a Calcined Waste Oyster Shell. *Water* **2017**, *9*, 661. [\[CrossRef\]](#)
41. Bhatnagar, A.; Sillanpää, M. A review of emerging adsorbents for nitrate removal from water. *Chem. Eng. J.* **2011**, *168*, 493–504. [\[CrossRef\]](#)
42. Nhung, N.T.H.; Long, V.D.; Fujita, T. A Critical Review of Snail Shell Material Modification for Applications in Wastewater Treatment. *Materials* **2023**, *16*, 1095. [\[CrossRef\]](#)
43. Sharma, A.; Devi, I.; Singh, R. A review on role of Molluscan shells in the removal of pollutants from aquatic water bodies. *Ecol. Environ. Conserv.* **2020**, *27*, 615–621.
44. Summa, D.; Lanzoni, M.; Castaldelli, G.; Fano, E.A.; Tamburini, E. Trends and Opportunities of Bivalve Shells' Waste Valorization in a Prospect of Circular Blue Bioeconomy. *Resources* **2022**, *11*, 48. [\[CrossRef\]](#)
45. Vandeginste, V. Food waste eggshell valorization through development of new composites: A review. *Sustain. Mater. Technol.* **2021**, *29*, e00317. [\[CrossRef\]](#)
46. Mahari, W.A.W.; Waiho, K.; Azwar, E.; Fazhan, H.; Peng, W.; Ishak, S.D.; Tabatabaei, M.; Yek, P.N.Y.; Almomani, F.; Aghbashlo, M.; et al. A state-of-the-art review on producing engineered biochar from shellfish waste and its application in aquaculture wastewater treatment. *Chemosphere* **2022**, *288 Pt 2*, 132559. [\[CrossRef\]](#)
47. Thürer, M.; Tomašević, I.; Stevenson, M.; Qu, T.; Huisingh, D. A systematic review of the literature on integrating sustainability into engineering curricula. *J. Clean. Prod.* **2018**, *181*, 608–617. [\[CrossRef\]](#)
48. Bellei, P.; Torres, I.; Solstad, R.; Flores-Colen, I. Potential Use of Oyster Shell Waste in the Composition of Construction Composites: A Review. *Buildings* **2023**, *13*, 1546. [\[CrossRef\]](#)
49. Koviessen, S.; O'Sullivan, A.; Gholami, M.; Vining, M.; de Vries, T. Physical and chemical parameters of various waste materials for living roof systems: A critical review. *Ecol. Eng.* **2023**, *194*, 107013. [\[CrossRef\]](#)
50. Gholami, M.; O'Sullivan, A.D.; Mackey, H.R. Nutrient treatment of greywater in green wall systems: A critical review of removal mechanisms, performance efficiencies and system design parameters. *J. Environ. Manag.* **2023**, *345*, 118917. [\[CrossRef\]](#)
51. Begum, S.; Yuhana, N.Y.; Saleh, N.M.; Kamarudin, N.H.N.; Sulong, A.B. Review of chitosan composite as a heavy metal adsorbent: Material preparation and properties. *Carbohydr. Polym.* **2021**, *259*, 117613. [\[CrossRef\]](#)
52. Burnham, J.F. Scopus database: A review. *Biomed. Digit. Libr.* **2006**, *3*, 1. [\[CrossRef\]](#)
53. Prancutė, R. Web of Science (WoS) and Scopus: The Titans of Bibliographic Information in Today's Academic World. *Publications* **2021**, *9*, 12. [\[CrossRef\]](#)
54. Fritzen, R.R.; Benetti, A.D. Phosphorus removal in domestic wastewater treatment plant by calcined eggshell. *Water Sci. Technol.* **2021**, *84*, 995–1010. [\[CrossRef\]](#)
55. Den, C.; Mariquit, E.G.; Kurniawan, W.; Hinode, H. Phosphate removal from wastewater using calcium silicate hydrate synthesized from lake sediment and bivalve shell. *J. Chem. Eng. Jpn.* **2020**, *53*, 287–295. [\[CrossRef\]](#)
56. Nguyen, T.A.H.; Ngo, H.H.; Guo, W.S.; Nguyen, T.T.; Vu, N.D.; Soda, S.; Nguyen, T.H.H.; Nguyen, M.K.; Tran, T.V.H.; Dang, T.T.; et al. White hard clam (*Meretrix lyrata*) shells as novel filter media to augment the phosphorus removal from wastewater. *Sci. Total. Environ.* **2020**, *741*, 140483. [\[CrossRef\]](#)
57. de Almeida, M.L.S.; Lima, A.C.; Nagahama, K.d.J.; Santos, T.S. Application of the Southwell Plot method to determine equilibrium time in phosphate adsorption. *J. Contam. Hydrol.* **2021**, *242*, 103841. [\[CrossRef\]](#)
58. Souza, T.A.; Mascarenhas, A.J.S.; Andrade, H.M.C.; Santos, T.S.M. Combining Sewage Sludge and Clam Shell Waste to Prepare Adsorbents for Efficient Phosphorous Removal. *Water Air Soil Pollut.* **2018**, *229*, 383. [\[CrossRef\]](#)
59. Hyland, K. Enter the dragon: China and global academic publishing. *Learn. Publ.* **2023**, *36*, 394–403. [\[CrossRef\]](#)
60. Daudzai, Z.; Dolphen, R.; Thiravetyan, P. Simultaneous Removal of Phosphate and Nitrate from Synthetic and Real Wastewater by *Meretrix lusoria* as an Efficient and Novel Material. *Water Air Soil Pollut.* **2021**, *232*, 186. [\[CrossRef\]](#)
61. Feng, M.; Li, M.; Zhang, L.; Luo, Y.; Zhao, D.; Yuan, M.; Zhang, K.; Wang, F. Oyster Shell Modified Tobacco Straw Biochar: Efficient Phosphate Adsorption at Wide Range of pH Values. *Int. J. Environ. Res. Public Health* **2022**, *19*, 7227. [\[CrossRef\]](#)
62. Pérez, S.; Muñoz-Saldaña, J.; Garcia-Nunez, J.A.; Acelas, N.; Flórez, E. Unraveling the Ca–P species produced over the time during phosphorus removal from aqueous solution using biocomposite of eggshell-palm mesocarp fiber. *Chemosphere* **2022**, *287 Pt 3*, 132333. [\[CrossRef\]](#)
63. Salim, N.A.A.; Fulazzaky, M.A.; Puteh, M.H.; Khamidun, M.H.; Yusoff, A.R.M.; Abdullah, N.H.; Fulazzaky, M.; Zaini, M.A.A. Mass Transfer Kinetics and Mechanisms of Phosphate Adsorbed on Waste Mussel Shell. *Water Air Soil Pollut.* **2022**, *233*, 223. [\[CrossRef\]](#)
64. Salim, N.A.A.; Fulazzaky, M.A.; Zaini, M.A.A.; Puteh, M.H.; Khamidun, M.H.; Yusoff, A.R.M.; Abdullah, N.H.; Ahmad, N.; Lazim, Z.M.; Nuid, M. Phosphate Removal from Wastewater in Batch System Using Waste Mussel Shell. *Biointerface Res. Appl. Chem.* **2020**, *11*, 11473–11486. [\[CrossRef\]](#)
65. Abdullah, N.H.; Yaacob, M.S.S.; Rani, N.A.I.; Azman, T.M.F.H.T.; Sumawan, M.N.I.; Hamid, N.B.; Salim, N.A.A.; Kaamin, M.; Kadir, M.A.A.; Ahmad, N.; et al. Phosphate Adsorption from Synthetic Aqueous Solutions by Waste Mussel Shell—Kinetics and Isotherms Studies. *Int. J. Nanoelectron. Mater.* **2021**, *14*, 1–10.
66. Salim, N.A.A.; Puteh, M.H.; Yusoff, A.R.M.; Abdullah, N.H.; Fulazzaky, M.A.; Arman, M.A.Z.R.; Khamidun, M.H.; Zaini, M.A.A.; Syafiuddin, A.; Ahmad, N.; et al. Adsorption isotherms and kinetics of phosphate on waste mussel shell. *Malays. J. Fundam. Appl. Sci.* **2020**, *16*, 393–399. [\[CrossRef\]](#)

67. Khamidun, M.H.; Ali, U.F.M.; Abdullah, S. Calculation of Filter Lifetime Using Empirical Model Applied to Hydrodynamic Column for Phosphate Removal from Greywater. *Int. J. Eng. Technol.* **2018**, *7*, 11–14. [\[CrossRef\]](#)
68. Zukri, N.I.; Khamidun, M.H.; Sapire, M.S.; Abdullah, S.; Rahman, M.A.A. Lake Water Quality Improvement by Using Waste Mussel Shell Powder as an Adsorbent. *IOP Conf. Ser. Earth Environ. Sci.* **2017**, *140*, 012057. [\[CrossRef\]](#)
69. Xiong, J.; Qin, Y.; Islam, E.; Yue, M.; Wang, W. Phosphate removal from solution using powdered freshwater mussel shells. *Desalination* **2011**, *276*, 317–321. [\[CrossRef\]](#)
70. Detho, A.; Daud, Z.; Rosli, M.A.; Awang, H.; Bin Ridzuan, M.B.; Halim, A.A.; Bin Tajarudin, H.A. Comparison study of COD and ammoniacal nitrogen adsorption on activated coconut shell carbon, green mussel (*Perna viridis*), zeolite and composite material in stabilized landfill leachate treatment. *Desalination Water Treat.* **2021**, *220*, 101–108. [\[CrossRef\]](#)
71. Detho, A.; Daud, Z.; Rosli, M.A.; Awang, H. Reduction of COD and ammoniacal nitrogen from stabilized landfill leachate by using green mussel and zeolite as composite adsorbent. *J. Air Waste Manag. Assoc.* **2022**, *72*, 69–75. [\[CrossRef\]](#)
72. Daud, Z.; Detho, A.; Rosli, M.A.; Abubakar, M.H.; Samo, K.A.; Rais, N.F.M.; Halim, A.A.; Tajarudin, H.A. Ammoniacal nitrogen and COD removal from stabilized landfill leachate using granular activated carbon and green mussel (*Perna viridis*) shell powder as a composite adsorbent. *Desalination Water Treat.* **2020**, *192*, 111–117. [\[CrossRef\]](#)
73. Feng, Y.; Luo, Y.; He, Q.; Zhao, D.; Zhang, K.; Shen, S.; Wang, F. Performance and mechanism of a biochar-based Ca-La composite for the adsorption of phosphate from water. *J. Environ. Chem. Eng.* **2021**, *9*, 105267. [\[CrossRef\]](#)
74. Feng, Y.; Zhao, D.; Qiu, S.; He, Q.; Luo, Y.; Zhang, K.; Shen, S.; Wang, F. Adsorption of Phosphate in Aqueous Phase by Biochar Prepared from Sheep Manure and Modified by Oyster Shells. *ACS Omega* **2021**, *6*, 33046–33056. [\[CrossRef\]](#)
75. Adhikari, R.A.; Krishna, K.B.; Sarukkalige, R. Evaluation of phosphorus adsorption capacity of various filter materials from aqueous solution. *Adsorpt. Sci. Technol.* **2016**, *34*, 320–330. [\[CrossRef\]](#)
76. Chen, J.; Cai, Y.; Clark, M.; Yu, Y. Equilibrium and kinetic studies of phosphate removal from solution onto a hydrothermally modified oyster shell material. *PLoS ONE* **2013**, *8*, e60243. [\[CrossRef\]](#)
77. Chen, W.-T.; Lin, C.-W.; Shih, P.-K.; Chang, W.-L. Adsorption of phosphate into waste oyster shell: Thermodynamic parameters and reaction kinetics. *Desalination Water Treat.* **2012**, *47*, 86–95. [\[CrossRef\]](#)
78. Lai, S.-L. Structure characterization and dephosphorization effect analysis of oyster shell-silica micropowder waste water dephosphorization materials. *Chin. J. Struct. Chem.* **2010**, *29*, 33–38.
79. Hwang, C.-C.; Weng, C.-H. Key factors contributing to simultaneous nitrification-denitrification in a biological aerated filter system using oyster shell medium. *Environ. Prot. Eng.* **2017**, *43*, 75–86. [\[CrossRef\]](#)
80. Han, Z.; Li, C.; Fan, R.; Lin, X.; Liu, D.; Wang, S.; Zhu, S.; Ye, Z. Ammonia Nitrogen Removal Using Oyster Shell as Alkalinity-Releasing Media in a Biological Nitrification System. *Trans. ASABE* **2017**, *60*, 1721–1728. [\[CrossRef\]](#)
81. Yen, H.Y.; Chou, J.H. Water purification by oyster shell bio-medium in a recirculating aquaponic system. *Ecol. Eng.* **2016**, *95*, 229–236. [\[CrossRef\]](#)
82. Wang, Z.; Dong, J.; Liu, L.; Zhu, G.; Liu, C. Study of oyster shell as a potential substrate for constructed wetlands. *Water Sci. Technol.* **2013**, *67*, 2265–2272. [\[CrossRef\]](#)
83. Liu, H.-Y.; Chen, S. Building a low-cost domestic wastewater reclamation system using local agricultural waste in Kinmen islands, Taiwan. *Paddy Water Environ.* **2017**, *15*, 809–819. [\[CrossRef\]](#)
84. Feng, Y.; Li, X.; Yu, Y.; Qi, J.; Jia, X.; Wang, J.; Li, X. Production of unburned calcium silicon filter material (UCSFM) from oyster shell and its performance investigation in an A/O integrated biological aerated filter reactor (A/O-BAF). *RSC Adv.* **2016**, *6*, 85324–85332. [\[CrossRef\]](#)
85. Shih, P.-K.; Chang, W.-L. The effect of water purification by oyster shell contact bed. *Ecol. Eng.* **2015**, *77*, 382–390. [\[CrossRef\]](#)
86. Azimi, S.M.; Malakootian, M.; Yaghmaeian, K.; Ahmadian, M.; Rahimi, S. Studying the efficiency of a biological aerated filter (BAF) with oyster Media on improving the quality of effluent produced by treatment plants. *Fresenius Environ. Bull.* **2014**, *23*, 2401–2406.
87. Wang, Z.; Dong, J.; Liu, L.; Zhu, G.; Liu, C. Screening of phosphate-removing substrates for use in constructed wetlands treating swine wastewater. *Ecol. Eng.* **2013**, *54*, 57–65. [\[CrossRef\]](#)
88. Liu, Y.-X.; Yang, T.O.; Yuan, D.-X.; Wu, X.-Y. Study of municipal wastewater treatment with oyster shell as biological aerated filter medium. *Desalination* **2010**, *254*, 149–153. [\[CrossRef\]](#)
89. Chen, J.; Zuo, K.; Li, Y.; Huang, X.; Hu, J.; Yang, Y.; Wang, W.; Chen, L.; Jain, A.; Verduzco, R.; et al. Eggshell membrane derived nitrogen rich porous carbon for selective electrosorption of nitrate from water. *Water Res.* **2022**, *216*, 118351. [\[CrossRef\]](#)
90. Cao, H.; Wu, X.; Syed-Hassan, S.S.A.; Zhang, S.; Mood, S.H.; Milan, Y.J.; Garcia-Perez, M. Characteristics and mechanisms of phosphorous adsorption by rape straw-derived biochar functionalized with calcium from eggshell. *Bioresour. Technol.* **2020**, *318*, 124063. [\[CrossRef\]](#)
91. Bus, A.; Karczmarczyk, A.; Baryła, A. Calcined Eggshell as a P Reactive Media Filter—Batch Tests and Column Sorption Experiment. *Water Air Soil Pollut.* **2019**, *230*, 20. [\[CrossRef\]](#)
92. Santos, A.F.; Arim, A.L.; Lopes, D.V.; Gando-Ferreira, L.M.; Quina, M.J. Recovery of phosphate from aqueous solutions using calcined eggshell as an eco-friendly adsorbent. *J. Environ. Manag.* **2019**, *238*, 451–459. [\[CrossRef\]](#)
93. Guo, Z.; Li, J.; Guo, Z.; Guo, Q.; Zhu, B. Phosphorus removal from aqueous solution in parent and aluminum-modified eggshells: Thermodynamics and kinetics, adsorption mechanism, and diffusion process. *Environ. Sci. Pollut. Res.* **2017**, *24*, 14525–14536. [\[CrossRef\]](#)

94. Abdullah, N.H.; Adnan, N.A.; Rashidi, N.F.N.M.; Yaacob, M.S.S.; Salim, N.A.A. Comparing the adsorption isotherms and kinetics of phosphate adsorption on various waste shells as adsorbent. *Water Pr. Technol.* **2022**, *17*, 974–985. [[CrossRef](#)]
95. Xiong, J.B.; Qin, Y.; Islam, E. Adsorptive removal of phosphate from aqueous solutions by waste snail and clam shells. *Environ. Eng. Manag. J.* **2015**, *14*, 1053–1058. [[CrossRef](#)]
96. Suwannasingha, N.; Kantavong, A.; Tunkijjanukij, S.; Aenglong, C.; Liu, H.-B.; Klaypradit, W. Effect of calcination temperature on structure and characteristics of calcium oxide powder derived from marine shell waste. *J. Saudi Chem. Soc.* **2022**, *26*, 101441. [[CrossRef](#)]
97. Majd, M.M.; Kordzadeh-Kermani, V.; Ghalandari, V.; Askari, A.; Sillanpää, M. Adsorption isotherm models: A comprehensive and systematic review (2010–2020). *Sci. Total Environ.* **2022**, *812*, 151334. [[CrossRef](#)]
98. Tsai, W.-T. Microstructural Characterization of Calcite-Based Powder Materials Prepared by Planetary Ball Milling. *Materials* **2013**, *6*, 3361–3372. [[CrossRef](#)]
99. Fulazzaky, M.A.; Salim, N.A.A.; Khamidun, M.H.; Puteh, M.H.; Yusoff, A.R.M.; Abdullah, N.H.; Syafiuddin, A.; Zaini, M.A.A. The mechanisms and kinetics of phosphate adsorption onto iron-coated waste mussel shell observed from hydrodynamic column. *Int. J. Environ. Sci. Technol.* **2021**, *19*, 6345–6358. [[CrossRef](#)]
100. Alidoust, D.; Kawahigashi, M.; Yoshizawa, S.; Sumida, H.; Watanabe, M. Mechanism of cadmium biosorption from aqueous solutions using calcined oyster shells. *J. Environ. Manag.* **2015**, *150*, 103–110. [[CrossRef](#)]
101. Ji, L.; Song, W.; Wei, D.; Jiang, D.; Cai, L.; Wang, Y.; Guo, J.; Zhang, H. Modified mussel shell powder for microalgae immobilization to remove N and P from eutrophic wastewater. *Bioresour. Technol.* **2019**, *284*, 36–42. [[CrossRef](#)]
102. Pai, S.; Kini, S.M.; Selvaraj, R.; Pugazhendhi, A. A review on the synthesis of hydroxyapatite, its composites and adsorptive removal of pollutants from wastewater. *J. Water Process. Eng.* **2020**, *38*, 101574. [[CrossRef](#)]
103. Azizian, S.; Eris, S. Adsorption isotherms and kinetics. In *Adsorption: Fundamental Processes and Applications*; Ghaedi, M., Ed.; Academic Press: Cambridge, MA, USA, 2021; Volume 33, pp. 445–509.
104. Pap, S.; Gaffney, P.P.; Bremner, B.; Sekulic, M.T.; Maletic, S.; Gibb, S.W.; Taggart, M.A. Enhanced phosphate removal and potential recovery from wastewater by thermo-chemically calcinated shell adsorbents. *Sci. Total. Environ.* **2022**, *814*, 152794. [[CrossRef](#)]

Disclaimer/Publisher’s Note: The statements, opinions and data contained in all publications are solely those of the individual author(s) and contributor(s) and not of MDPI and/or the editor(s). MDPI and/or the editor(s) disclaim responsibility for any injury to people or property resulting from any ideas, methods, instructions or products referred to in the content.