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A Comprehensive Review on Vegetable Waste Biosorbents for Sustainable Wastewater Treatment

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Abstract

Untreated wastewater, including both municipal and industrial wastewater, contaminates soil, surface water, and groundwater, posing a serious environmental risk. Innovative, economical, renewable, and ecologically safe wastewater treatment solutions are currently required. In order to improve wastewater treatment, a number of methods, including ion exchange, co-precipitation, adsorption, membrane separation, oxidation, and biochemical processes, are now being investigated for the production of bioactive components from vegetables. To remove impurities from wastewater, a variety of adsorbents are developed and used among which, bioadsorbents derived from waste biomass stand out for being economical, sustainable, renewable, and environmentally safe. This review examines vegetable-based biomass waste as a low-cost adsorbent for waste water treatment. Vegetable waste has garnered a lot of attention due to its abundance, high biocellulose content (21%), and affordability, with cassava, potato peels, and moringa seeds showing adsorption efficiencies of 85-90% for heavy metals and dyes.

The novelty of this review lies in consolidating fragmented findings on vegetable peel based biosorbents into a unified framework linking biomass composition to adsorption performance. Research gap- limited data on regeneration and reusability, absence of standardized protocols related to efficiency-comparison, and insufficient testing in real waste water matrices and at pilot scale. Future work should focus on surface modification techniques, long-term stability assessments, and integration into existing treatment infrastructure. Addressing the above-mentioned gaps is essential to moving vegetable-peel bioadsorbents from laboratory-scale promise to practical, large-scale application in heavy metal and dye removal from wastewater.

Keywords: Vegetable residues; Organic waste; Wastewater treatment; Water pollution; Sustainable practices

1. Introduction

Water contamination has worsened over the last several decades due to the unregulated discharge of household effluent, as well as agricultural and industrial waste, into water and soil. The contaminants can eventually filter into subsurface sources. Two of the most common contaminants are heavy metals and textile dyes (Karić et al., 2022). About 20% of the colors used in industry are released into effluents, and heavy metals are usually a consequence of industrial and medical waste. Both contaminants are extremely dangerous to human and environmental health, even at very low quantities. Due to the ineffectiveness of traditional wastewater treatment methods, these non-biodegradable contaminants persist in surface and groundwater sources and eventually end up in aquatic organisms (Aguilar-Rosero et al., 2022). Organic materials, medications, fertilizers, pesticides, chemicals from personal care products, and other micro-organics are among the additional water contaminants referred to as emerging contaminants. The composition of real wastewater differs significantly from that of synthetic wastewater in the respect that the later one is quite simple and more defined, specifically limited to composing the common laboratory chemicals glucose or acetate. Moreover, the organic matter carbon present in synthetic waste water is used for biodegradable research analysis. Although real wastewater contains more microbial mass, the solids in synthetic wastewater are quite minimal. The microbial elements of real wastewater are complex and cannot be replicated under laboratory conditions (O'Flaherty and Gray, 2013).

Most of these compounds are uncontrolled and produced by humans; the only way to detect them is using chromatography techniques combined with mass spectrometry (Bhattacharjee et al., 2020). Although they are prevalent in the environment at extremely low levels, their harmful effects are significant. These toxins can cause endocrine disruption, cancer, mutagenesis, reproductive and embryonic toxicity, and a variety of other long-term effects on aquatic life and human health (Tee et al., 2022). According to the United Nations Educational, Scientific and Cultural Organization, one in every nine people on Earth is forced to drink water from contaminated sources. More than 2 million tons of sewage and other effluents are discharged into bodies of water daily. Thus, it is crucial to prioritize therapies that are both inexpensive and environmentally friendly (Matei et al., 2021).

Certain methodologies like adsorption (Physical vs. chemical processes, thermodynamic driving forces, isotherm models, and applications), biosorption (Non-metabolic accumulation on biomass, mechanisms *viz.,* complexation, ion exchange, precipitation, their advantages, and limitations) and bioadsorbents (Classification by source *viz.,* agricultural waste, microbial, algal, engineered, their structural features, functional groups, preparation methods, and characterization) are used to overcome environmental pollution challenges. A range of methods, including chemical, physical, and biological ones, have been developed to treat wastewater before it is released into rivers, seas, or other bodies of water. Their use depends on the process's cost, the environment's suitability, and the specific effluent levels allowed (Chong et al., 2023). The processes include adsorption, microbial reduction, flotation, electrolysis, filtration, ion exchange, and bioremediation. When an adsorbate or contaminant is retained on the surface of an adsorbent (biomaterial), a thin layer of molecules or atoms is formed due to residual contacts, such as covalent bonds or Van Der Waals forces. This phenomenon is known as biosorption (Mathew et al., 2023). In wastewater treatment, biosorption is the process of forming a mono- or multilayer by bringing the liquid phase and the solid surface into contact, either through a chemical (chemisorption) or physical (physisorption) process. Adsorbent biomaterials draw heavy metals and other charged impurities by ion exchange and electrostatic interactions, just like synthetic resins do. Because agricultural by-products contain substantial amounts of cellulose and lignocellulose, they are recommended as an affordable alternative to conventional adsorbents (Bhattacharjee et al., 2020; Ziarati et al., 2020). Grains, seeds, fruits, vegetables, herbage, and forage are among the most prevalent waste products in the food and agricultural sectors. These waste materials have significant potential as adsorbent that may effectively clean contaminated effluents (Gupta et al., 2022). However, several considerations must be made to achieve the best possible removal of contaminants, including production volume, the chemical and physical properties of the bioresidues, and operational parameters such as pH, adsorbent dose, particle size, temperature, adsorption kinetics, and isothermal behavior. Vegetable waste-derived bioadsorbents have a broad range of uses in wastewater treatment (Kwikima et al., 2021). These adsorbents possess high appeal and are economically feasible for extensive applications. Vegetable-derived waste biosorbents have been employed to eliminate various water contaminants, including heavy metals, radioactive chemicals, colors, organic compounds, oils, and pharmaceutical waste (Mishra et al., 2021). One of the research gaps is validation of waste water under realistic wastewater conditions along with limited data on regeneration and reusability of vegetable waste biosorbents for removing heavy metals, dyes and other pollutants. Though it is already mentioned in various studies earlier, but only few have evaluated their regeneration and reuse potential. Future research should focus on identifying some techniques that can be cost effective and identify the potential of various vegetable based biosorbents for reusing again over several cycles with standardized efficiency-comparison protocols. The present work aims to categorize data on biosorbents derived from vegetable waste for wastewater treatment.

2. Impact of wastewater on human health

Contaminated water poses serious risks to human health. According to the UNESCO 2021 World Water Development Report, around 829,000 people die each year from diarrhea caused by contaminated drinking water, inadequate sanitation, and poor hand hygiene (Chowdhary et al., 2020). According to evidence from Palestine, those who drink untreated municipal water are more likely to get diseases like diarrhea than those who use desalinated and household-filtered water. A mere 8% of the population can access water more than 50 L per person per day, followed by 27% of the population can consume 20-50, and 65% of the population can consume 20L per person per day (Abuzerr et al. 2019). Water availability strongly correlates with diarrhea diseases, which has an odds ratio 2.58, meaning that the risk of contracting the diseases may be increased when water availability is poor. In addition, poor hygiene practices including, polluted drinking water, relate to diarrhea diseases, which has an odds ratio up to 2.40. Asside from diarrhea, polluted drinking water can result in a range of health issues, including gastrointestinal illnesses, typhoid fever, cholera, and dysentery. Tap water was found to be a significant contributor to gastrointestinal illness in a comparative analysis of tap, filtered, and bottled water (Sonone et al., 2020). Diseases, including cholera, trachoma, schistosomiasis, and helminthiasis, are more common where there is insufficient access to water and sanitary facilities. A definitive link has been established by research conducted in developing countries between contaminated water and cholera, the risk of cholera can be effectively reduced by employing home water treatment and storage technologies (Sankhla et al., 2018; Chowdhary et al., 2020). Malabsorption of nutrients can be impeded by gastrointestinal illnesses, which can be brought on by contaminated drinking water and unclean surroundings. Children are more prone to experiencing these impacts. Inhaling airborne pollutants from contaminated water can trigger respiratory ailments such as asthma and bronchitis. Exposure to hazardous substances, such as lead, mercury, and pesticides, can result in severe health issues, including neurological impairment, birth defects, and cancer (Ahmad et al., 2021).

Direct exposure to polluted water can cause skin irritation, itching, and rashes. Annually, over 2 million individuals globally are affected by diarrheal illnesses, primarily due to inadequate sanitation and contaminated drinking water, which accounts for almost 90% of fatalities, disproportionately impacting children (Haseena et al., 2017). Over 50 distinct diseases are caused by low drinking water quality, and 80% of diseases and 50% of child mortality worldwide are directly related to it. Numerous health problems, including diarrhea, skin conditions, malnourishment, and even cancer and other disorders linked to water contamination, are brought on by pollution (Proshad et al., 2018). Therefore, it is necessary to examine how water pollution affects people's health, including the range of illnesses they contract, and explain why clean drinking water is important. This has significant theoretical and applied ramifications for accomplishing goals related to sustainable development. While there are many books on water pollution and a particular disease, there aren't many studies that examine how water pollution affects people's health and the range of diseases that can result (Warren-Vega et al., 2023). The effect of heavy metals on human health has been depicted in **Fig 1-2.**

3. Vegetable-based waste materials and Sustainable developmemt goals

Vegetable waste products are the residual materials that are produced as a result of the production, processing, and consumption of vegetables. Approximately 80% of the generated food waste products, including vegetable waste products, are disposed of in landfills. The different causes of vegetable waste are depicted in **Fig 3-5**. These encompass agricultural remnants, peels, foliage, stalks, and additional organic substances. Due to the growing population, the demand for food and vegetables has escalated to billions of tons annually (Ganesh et al., 2022). The proximate and elemental analyses of different vegetables, along with their waste volume, are presented in Table 1. This signifies the production of substantial quantities of vegetable waste, including peels, leaves, stalks, seeds, and stones. Furthermore, substantial amounts of garbage can cause environmental damage, resulting in additional expenses for waste management. Commonly, biosorbent needs an active site that can remove pollutants from wastewater. Fortunately, vegetable wastes contain chemical compositions and functional groups as active sites that play a role in the biosorption process, including cellulose, hemicellulose, lignin, hydroxyl, carboxyl, amino, and sulfhydryl (Bayram et al., 2021). Previous study presented that composite honeycomb porous L-cysteine has multiple functional groups, including amino, thiol, carboxyl, and hydroxyl. These functional groups can adsorb uranium element [U(VI)] from radioactive wastewater up to 90% (Zhou et al., 2025). The *Allium cepa* biomass, which contains carboxyl, hydroxyl, amino, and carbonyl groups was also achieved 99% to remove several elements such as Cu(II), Cd(II), and Pb(II). It indicates that biomass from vegetable wastes can provide functional groups for biosorption process, either physisorption or chemisorption. In addition, since the vegetable waste contain around 50% carbon, it can be converted into composite or activated carbons by applying thermal treatment methods in an inert atmosphere at high temperatures. Vegetable waste biosorbents are currently being demonstrated to be an effective way to remove contaminants from wastewater. Many vegetables can be utilized as biosorbents to clean wastewater, such as potatoes, brinjal, cabbage, cauliflower, radish, beetroot, capsicum, and carrot (Jiménez-Moreno et al., 2020).

Biosorbents made from vegetable waste provide an alternative solution that supports several SDGs. In addition to supporting circular economy ideas under SDG 12 (Responsible Consumption and Production), they contribute to SDGs 6 (Clean Water and Sanitation) and 13 (Climate Action) by repurposing waste materials for air and water purification. By using them, pollution is reduced, biodiversity is preserved (SDGs 14 and 15), health outcomes are improved (SDG 3), and innovation is encouraged (SDG 9). These biosorbents enable affordable, clean energy (SDG

7) through cooperative collaborations (SDG 17), providing a comprehensive framework for societal well-being and environmental stewardship. Effective waste management, including the use of vegetable waste biosorbents, can contribute to building resilient and inclusive societies by reducing environmental pollution and promoting sustainable practices (SDG 16). The connection of the biobased adsorbent linkage has been summarized in Fig. 6.

Thirteen of the seventeen UN Sustainable Development Goals are directly supported by vegetable-waste biosorption, which uses agricultural residues to remove pollutants from soil and water. By eliminating pathogens, dyes, and heavy metals from wastewater and drinking water in environments with limited resources, it most significantly supports SDG 6 (Clean Water and Sanitation). Additionally, it promotes SDG 8 (Economic Growth) by creating jobs in rural biosorption firms, SDG 3 (Health) by avoiding waterborne infections, and SDG 12 (Responsible Consumption) through waste valorization and circular economy concepts. By eliminating methane emissions from landfill waste and substituting energy-intensive synthetic adsorbents, it also advances SDG 13 (Climate Action). Food security (SDG 2), gender equality through women-led enterprises (SDG 5), industrial innovation (SDG 9), decreased inequality (SDG 10), restoration of marine and land ecosystems (SDGs 14–15), and strengthened institutions and international cooperation (SDGs 16–17) are all made possible by vegetable-waste biosorption in addition to these primary contributions (Montiel et al., 2021; Mishra et al., 2023). The technique is an affordable, locally driven solution that tackles several sustainability issues at once, and it is especially effective in low-income nations where agricultural leftovers are plentiful and traditional water treatment infrastructure is scarce.

4. Synthesis and characterization of a vegetable waste-derived bioprocess tool

Vegetable waste is a plentiful and highly prolific source of polymers. Natural vegetables are bio-polymer sources that contain abundant cellulose. The waste from these vegetables can be categorized into many sections, including peel, pomace, seeds, segment peel, and pulp. These wastes possess hydrophilic properties, enabling them to have both a high chemical surface reactivity and strong mechanical strength (Karić et al., 2022).

4.1 Synthesis of vegetable waste-derived biosorbents

Natural vegetable matter is a well-known feedstock for activated carbon production due to its high cellulose content. It is also considered a promising source of water-purification absorbents (Serage et al., 2022). They can efficiently hold organic contaminants during a variety of processes, such as aeration, filtration, desalination, and sedimentation, thanks to their high porosity. Nowadays, a number of processes, including hydrothermal carbonization, chemical explosion, and precipitation, are used to produce biosorbents, including nano cellulose, carbon foam, and modified and functionalized adsorbents (Yadav et al., 2020). Several processes have been used to make biosorbents from vegetable waste, including hydrothermal activation, pyrolysis, precipitation, and carbonisation. The activated carbons are produce by treating the adsorbents with acids and alkalis such as NaOH, KOH, $ZnCl_2$, $FeCl_3$, and H_3PO_4 The nature of the vegetable waste and its physiochemical parameters determine the type of activation process and activating substance used (Karić et al., 2022). These biosorbents are characterized by their high cellulose, hemicellulose, and lignocellulose content, which provide excellent sorption properties for removing various pollutants, including heavy metals, dyes, pharmaceuticals, and industrial contaminants (Lam et al., 2020; Foo and Hameed, 2012).

4.1.1. Physical Activation Methods

4.1.1.1 Steam Activation

One of the most popular physical activation methods for converting biochar derived from vegetable waste into activated carbon with improved adsorption qualities is steam activation. This process involves exposing carbonized vegetable waste material to high-temperature steam (usually between 700 and 927 °C) in a controlled setting. This oxidizes the carbon structure, forming new micropores and enlarging existing ones. By reacting with the char surface, the steam serves as a gasification medium, eliminating interior carbon atoms, thereby enhancing the final material's specific surface area and porosity (Sajjadi et al., 2019; Guo and Lua, 2002).

4.1.1.2 Oil Palm Kernel Shell

A central composite design methodology was used to examine conventional steam activation of oil palm kernel shell (Zainal et al., 2019). To produce biochar, the oil palm kernel shell was first carbonized at 725 °C for 80 minutes. This was followed by 10 minutes of steam activation. Under ideal condition, the resultant activated carbon showed a fixed carbon content of 19.39% during wastewater treatment over 90 minutes of adsorption time, along with 32.02% chemical oxygen demand (COD) removal efficiency and 61.15% color removal efficiency. This study showed that steam activation effectively improved the material's porosity and adsorption capacity.

A thorough investigation examined how steam activation and pyrolysis temperature affected the structural characteristics of biochar produced from apple trash (Sokker et al., 2024). Samples of biochar were created at temperatures between 300 and 800 degrees Celsius, and some samples underwent concomitant steam activation. The results showed that pyrolysis at a lower temperature (300 °C) produced biochar with an ordered structure and functional groups. On the other hand, biochar produced via steam activation and high-temperature pyrolysis (700–800 °C) exhibited much higher microporosity and specific surface area, reaching a maximum value of 725 $m^2 g^{-1}$ for some samples. The disorder index (ID/IG ratio) increased from 0.50 to 0.55 following the steam activation procedure, suggesting structural modifications that enhance adsorption capability for environmental remediation applications. Steam activation is caused by complex interactions between the biochar surface and water molecules at high temperatures. Compared to other physical activation techniques, steam produces a reactive environment that results in a smaller microporosity, with average pore diameters usually falling between 0.55 and 0.6 nm. Steam-activated biochar is very useful for adsorbing specific pollutants via size-selective mechanisms due to its narrow pore size distribution (Maneerung et al., 2016).

4.1.1.3 CO_2 Activation

Another significant physical activation technique is CO_2 activation, which uses carbon dioxide gas at high temperatures (usually 700–800 °C) to create porous structures in carbon material generated from vegetable waste. CO_2 functions as a gasification medium that combines with the carbon matrix to form and expand pores, much like steam activation. However, compared to steam activation, which mostly results in microporous structures, CO_2 activation usually yields a higher percentage of mesopores (pores with a diameter 2–50 nm) (Liew et al., 2019; Pallarés et al., 2018).

4.1.1.4 Orange Peel Waste with Microwave-Assisted Activation

Orange peel waste (OPW) was converted into microwave-activated biochar (MAB) using a novel microwave pyrolysis technique that combined microwave heating with concurrent CO_2 activation (Yek et al., 2020). In this one-step procedure, carbonization and activation were carried out concurrently in an inert atmosphere at temperatures above 800 °C, with a quick heating rate of 15–120 °C/min and a process duration of just 15 minutes. The resulting activated biochar had a fixed carbon content of 58.6–61.2 weight percent, a Brunauer Emmett Teller (BET) surface area of 158.5–305.1 $m^2\ g^{-1}$, a mass yield of 31–44 weight percent, and remarkably low H/C and O/C ratios (0.3 and 0.2, respectively). CO_2-activated MAB demonstrated 91 mg/g adsorption efficiency and 89–93% dye removal when tested for Congo Red dye removal. According to the study, CO_2 activation created more micropores than steam activation, which made it possible for smaller dye molecules to be effectively adsorbed.

4.1.1.4 Corncob-Based Activated Carbon

To increase specific surface area, a study on the conversion of waste biomass (corncobs, coconut shells, walnuts, and pistachio husks) used CO_2 activation at 800 °C for 0.5 hours (Ivancev-Tumbas et al., 2023). When compared to the raw biochar, the surface area increased dramatically from four to over ten times as a result of the CO2 activation process. Of all the materials studied, corncob-derived activated carbon had the largest specific surface area of 725 $m^2\ g^{-1}$. The removal of model contaminants, such as Rhodamine B dye (99% removal at a dye/AC ratio of 0.0017) and chromium (VI) ions (69% removal at a ratio of 0.0028), was then assessed using this activated carbon. The better dye removal performance proved that CO2-activated materials are good at adsorbing organic contaminants.

4.1.2 Chemical Activation Methods

4.1.2.1 H_3PO_4 (Phosphoric Acid) Activation

The most popular chemical activating agent for creating activated carbon from vegetable waste and other lignocellulosic biomass is phosphoric acid (H_3PO_4). Its ease of recovery, minimal environmental impact, increased carbon production, and distinct pore development mechanisms are the reasons for this preference. Di-phosphorus penta oxide (P_4O_{10}), a potent oxidant that combines with carbon to form new pores and widen old ones, is produced when the acid is dehydrated at high temperatures during H_3PO_4 chemical activation. Furthermore, phosphoric acid produces phosphate and polyphosphate bridges that bind biopolymer fragments, enhancing mechanical properties and preventing material contraction during thermal processing. With carbon yields of 26.1–85% and adsorption capacities varying from 2.5 to 89.29 mg/g, the surface area of activated carbon generated by H_3PO_4 activation from lignocellulosic biomass usually ranges from 456.1 to 2806 $m^2\ g^{-1}$ (Budinova et al., 2006; Yahya et al., 2022).

4.1.2.2 Bamboo Waste

A two-stage activation technique was used to create activated carbon from bio-waste materials of Bambusa vulgaris (bamboo): thermal treatment for physical activation and H3PO4 for chemical activation (Kibami and Hesielie, 2022). Physical and chemical analyses, such as pH measurement, apparent density determination, Boehm titration for surface functional groups, iodine number analysis, proximate analysis, SEM examinations, and FTIR spectroscopy, were used to evaluate the activated carbon. For the same biomass precursor, BET analysis showed that H_3PO_4 activation yielded a greater BET surface area than HNO_3 activation. The H_3PO_4-activated bamboo carbon exhibited a high iodine absorption capacity, suggesting the development of a well-developed porous structure. Bamboo waste-derived H_3PO_4-activated carbon is an efficient low-cost adsorbent for water purification applications, as demonstrated by the synthesized adsorbent's ability to remove pollutants from water.

4.1.2.3 Sago Waste

Along with various activators ($ZnCl_2$, KOH, and $KMnO_4$), chemical activation of sago waste utilizing H_3PO_4 was assessed (Marawo et al., 2021). In this work, 25 mL of a 20% H3PO4 solution was mixed with 5 g of carbonized sago waste, heated to 85 °C for 4 hours, and then heated to 600 °C for 3 hours. After that, H_3PO_4--activated carbon was repeatedly cleaned with warm distilled water (70 °C) until the pH was neutral. While $ZnCl_2$ activation created the largest specific surface area (546.61 $m^2\ g^{-1}$), H_3PO_4-activated sago carbon exhibited noteworthy surface chemical characteristics and showed good adsorption capability for a variety of pollutants. According to the study's findings, H_3PO_4 activation successfully altered the surface chemistry of carbons derived from vegetable waste, yielding acid functional groups suitable for specific adsorption applications.

4.1.2.4 KOH (Potassium Hydroxide) Activation

Another very powerful chemical activator that yields activated carbon with remarkable surface area and porosity properties is potassium hydroxide (KOH) (Yahya et al., 2022). There are two ways to carry out KOH activation: the carbonization-activation method, in which the material is first carbonized before KOH activation, and the impregnation-activation method, in which the biomass precursor is impregnated with concentrated KOH solution prior to heating. Comparison to H_3PO_4-activated materials, KOH-activated carbon usually reaches greater specific surface areas; some investigations have found values exceeding 1626 $m^2\ g^{-1}$. A highly porous carbonaceous structure is left behind when potassium molecules that generate a reactive environment for pore growth evaporate at higher temperatures as part of the KOH activation mechanism.

4.1.2.5 Olive Mill Wastewater-Derived Alperujo

KOH activation was used to create activated carbons from olive residue combined with oil and vegetable water (alperujo) at various KOH/carbon ratios utilizing both impregnation-activation and carbonization-activation techniques (Pérez-Cadenas et al., 2017). KOH-activated carbons showed type I isotherms, which are typical of microporous materials, according to N_2 adsorption-desorption isotherms. After KOH activation, a maximal specific surface area of 1626 $m^2\ g^{-1}$ was attained. When employing low KOH ratios, the resulting KOH-activated carbons showed comparable textural and chemical characteristics regardless of the preparation technique, whereas higher KOH ratios resulted in more porous samples through carbonization. KOH-activated samples had oxygenated surface groups that mostly broke down as CO_2, indicating carboxylic acid, anhydride, and lactone groups, according to XPS and temperature-programmed desorption (TPD) studies. KOH-activated carbons produced capacitance values dependent linearly on surface area, according to the electrochemical evaluation, indicating their suitability for supercapacitor applications.

4.1.2.6 Rice Husk with Combined H_3PO_4/KOH Activation

For the manufacture of activated carbon from rice husk, a unique method used a mixture of KOH and H3PO4 as an activation agent (Zan et al., 2022). Different volumes of individual activating agents and mixed solutions (H_3PO_4 at 7 mL, KOH 3 M at 10 mL, and combined 1:1 by volume at 14 mL) were applied to rice husk char (0.3 g). According to FTIR research, the mixed agent enhanced the surface area of the rice husk char by partially decomposing chemical compounds on its surface. The highest specific capacitance values were 73.5 F/g for H_3PO_4 activation, 124.2 F/g for KOH activation (3 M), and an astounding 241.3 F/g for the combined H_3PO_4/KOH mixed activation. The combined activation system showed that KOH and H3PO4 function in concert. KOH produces highly reactive carbonaceous surfaces that lead to improved porosity and electrochemical performance, while H_3PO_4 catalyzes depolymerization and forms phosphate bridges.

4.1.2.7 HNO_3 (Nitric Acid) Activation

An acidic activating agent, nitric acid (HNO_3), adds oxygen-containing surface complexes to the carbon matrix, altering the activated carbon's porosity and surface area. By oxidizing the carbon surface, HNO_3 treatment produces hydroxyl, phenolic, and carboxylic acid groups that increase ion-exchange characteristics and metal ion removal from aqueous solutions. HNO_3-activated materials are very useful for heavy metal adsorption because of the process, which breaks C-C bonds and introduces polar functional groups (Lesaoana et al., 2019; Kumar et al., 2013).

4.1.2.8 Bamboo Waste Comparison Study

HNO_3 treatment was compared with H_3PO_4 activation in a study on bamboo waste chemical activation (Kibami and Hesielie, 2022). Activated carbons treated with HNO_3 introduced carboxyl groups and formed oxygen complexes at distinctive wavenumbers, as determined by FTIR. Physical analysis revealed that HNO_3 activation resulted in a high iodine number, suggesting that the acid treatment added more acidic surface oxygen groups. increased apparent densities were shown by both HNO_3 and H_3PO_4-activated bamboo carbons, resulting in increased volume activity and higher-quality activated carbon. In contrast to H_3PO_4-activated samples, HNO_3-activated materials typically produced more micropores and fewer mesopores. The study found that while H_3PO_4 activation provides superior yield and structural preservation, HNO_3 activation is particularly appropriate for applications requiring acidic surface groups and heavy metal removal.

4.1.3 Combined and Novel Synthesis Methods

4.1.3.1 Microwave-Assisted Thermal Activation

With major benefits over traditional furnace-based methods, microwave technology has become a promising heating method for biosorbent synthesis. Compared to traditional conduction or convection heating, microwave heating offers volumetric heating via radiation, making it more energy-efficient. Compared to traditional processes that require more than an hour, this technology allows for faster heating rates (15–120 °C/min) and shorter process periods (usually 15 minutes). According to Pallarés et al., (2018), microwave-assisted activation can be used in conjunction with physical activation agents (such as steam or CO_2) in a one-step process that simultaneously activates and carbonizes, reducing energy and process time while boosting product yield.

4.1.3.2 Orange Peel Waste with Single-Step Microwave Activation

Orange peel waste was converted into microwave-activated biochar using a novel method that combined microwave-assisted pyrolysis with steam or CO_2 activation (Yek et al., 2020). Orange peel waste was simultaneously carbonized and activated in a single-step process using microwave heating at temperatures above 800 °C, with a heating rate of 15–120 °C/min and a processing duration of about 15 minutes. The mass yield of the microwave-activated biochar was 31–44 weight percent, the fixed carbon content was 58.6–61.2 weight percent, and the H/C and O/C ratios were 0.3 and 0.2, respectively. Crucially, the kind of activation had a major impact on the pore structure: steam activation created more mesopores (2–50 nm), whereas CO2 activation produced primarily micropores (less than 2 nm). Steam-activated MAB performed better (136 mg/g adsorption efficiency) than CO_2 activation (91 mg/g) when tested for Congo Red dye removal, resulting in 89–93% dye removal. This study showed that physical activation in conjunction with microwave technology provides a quick and energy-efficient technique to transform vegetable waste into high-performance adsorbents with adjustable pore shapes.

4.1.3.3 Chemical Surface Modification

Chemical surface modification strategies can improve vegetable waste-derived biosorbents beyond conventional activation procedures [22]. Chemical modification is the process of applying modifying chemicals (such chitosan, alginate, or H2SO4) to the adsorbent in order to change its surface properties and structure by adding new functional groups or elements. This method makes the material more successful for certain pollutant removal applications by increasing the number of active binding sites and improving its ion-exchange characteristics (Sokker et al., 2011).

A recent study created CHT/GVW-HS, a bioadsorbent made from green vegetable waste (lettuce leaves, Swiss chard stems, and cucumber peel) functionalized with chitosan and H_2SO_4 treatment (Aswad et al., 2024). The green vegetable waste was treated with H2SO4 acid and then combined with chitosan biopolymer for the synthesis. Methylene blue (MB) dye removal efficiency was maximized by optimizing the resultant adsorbent using Box-Behnken Design (BBD) statistical methods. With a maximum adsorption capacity that closely matched values seen in the literature for advanced adsorbents, the CHT/GVW-HS composite showed exceptional adsorption capabilities for cationic dyes. Electrostatic interactions, hydrogen bonding, π-π stacking, and n-π stacking between the dye molecules and the functionalized adsorbent surface were all part of the adsorption mechanism. This demonstrated the synergistic effects that result in superior adsorbents for dye removal in wastewater treatment applications when vegetable waste is combined with natural biopolymers like chitosan and subjected to chemical modification.

4.1.4 Synthesis Parameter Optimization and Selection

The best synthesis parameters for biosorbents made from vegetable waste depend on a number of variables, such as the type of pollutant that is sought, the equipment that is available, financial restrictions, and the characteristics of the target adsorbent (Foo and Hameed, 2012). Pyrolysis temperature (usually 400–900 °C), activation temperature (700–927 °C for physical activation, 500–800 °C for chemical activation), activation time (between 0.5 and 10 hours), impregnation ratio (usually 0.5:1 to 2:1) for chemical activators, and heating rate are important synthesis parameters that need to be optimized. Longer activation durations and higher pyrolysis temperatures often result in higher microporosity and specific surface areas, but they may also raise production costs and decrease carbon yield (Sokker et al., 2024; Kumar et al., 2013). Although they usually demand greater temperatures, physical activation techniques (such as steam and CO2) offer better environmental compatibility and lower activation chemical costs. Chemical activation techniques, especially H3PO4 and KOH, can produce more carbon at lower temperatures, but they need to be handled and recovered carefully. Although microwave-assisted techniques save a lot of energy and time, they necessitate the purchase of specialist equipment.

4.2 Characterization of vegetable-derived biosorbents

Several characterization approaches are used to assess a material's adsorption capability, physical and chemical characteristics, and interactions with contaminants. These methods include X-ray diffraction, Barrett–Joyner–Halenda (BJH), Brunauer–Emmett–Teller method (BET), Fourier transform infrared spectroscopy (FTIR), and others. The different characterization techniques for the treatment of wastewater are discussed below:

4.2.1 Fourier transmission infrared spectrometry (FTIR)

Fourier transforms Infrared spectroscopy can be used to examine the adsorption bands associated with the functional groups and crystalline disorder of vegetable-derived biosorbents. This technique allows for the identification of the molecules and functional groups found on the surface of biomaterials that interact with contaminants (Nyika and Dinka, 2023). FTIR is used to characterize a wide spectrum of biomass adsorbents. Some of them correspond to the hydroxyl groups formed by cellulose, hemicellulose, and lignin present in agricultural waste. Infrared (IR) regions are divided into four categories: near-IR, mid-IR, and far-IR. The near infrared (IR) spectrum, spanning from 14,000 to 4000 cm^{-1}, is characterized by changes in vibrational and rotational energy levels, as well as electron transitions (Das et al., 2020). The mid-IR range, ranging from 4000 to 400 cm^{-1}, shows changes in the fundamental vibrational modes of most compounds. The far-IR spectrum ranges from 400 to 20 cm^{-1} and varies in rotational energy levels (Bobde et al., 2021). Chanda et al., (2024) used the FTIR and SEM techniques to evaluate cauliflower leaf powder as a biosorbent for methylene blue adsorption from aqueous solution.

FTIR analysis identifies distinctive functional groups such as C-H stretches, O-H stretches (hydroxyl groups), C=O stretches (carbonyl groups), and N-H stretches (amino groups) in fruit and vegetable waste samples like apple peels, carrot peels, celery, and beetroot leaves. These functional groups show that the waste material contains proteins, organic acids, and non-starchy carbohydrates. According to Naumann et al., (1996), the process usually entails preparing samples as KBr pellets or employing attenuated total reflectance (ATR) accessories for direct surface examination. With a resolution of 4 cm^{-1}, spectra are captured within a wavenumber range of 4000 cm^{-1} to 500 cm^{-1}. To increase the signal-to-noise ratio, several scans, typically 100 or more, are combined (Smidt et al., 2002). Vegetable waste products are complex matrices that contain cellulose, hemicellulose, pectin, and other polysaccharides, as shown by the ensuing FTIR-ATR spectra (Amakura et al., 2006). Amino acid peaks at 1385 cm^{-1}, carboxyl groups, and aliphatic groups at 2930 cm^{-1} and 2850 cm^{-1} are examples of functional groups that exhibit distinctive signatures. These spectrum characteristics gradually alter throughout composting or decomposition processes; the loss of amino acid peaks and the diminishing intensity of aliphatic groups signify the humification and degradation of organic materials. When determining the maturity of compost and the amount of bioactive compounds in vegetable waste extracts, FTIR analysis is especially helpful. The method is a perfect complement to other characterization techniques because it can quickly and non-destructively evaluate complicated organic matrices. Furthermore, FTIR spectra can be used in conjunction with multivariate data analysis techniques to categorize various waste materials, differentiate between phases of decomposition, and forecast the humic acid content of final compost products (Sulaiman et al., 2022).

4.2.2 Brunauer–Emmett–Teller and Barrett–Joyner–Halenda (BET/BJH)

These techniques are applied to evaluate particulate matter, volume, and pore size as well as other surface characteristics of bioadsorbents. An inverse relationship between the pore radius and the multilayer thickness ratio is utilized by the BJH approach, whereas the BET method relied on the equilibrium adsorption isotherm at the adsorbate's boiling point (Monlau et al., 2015). BJH was utilized in order to ascertain the volume of micropores and mesopores present in vegetable waste. Ion integration in the adsorption process can be better understood with the help of BET, which allows for comparisons of any adjustments both before and after they have been made. BET surface area analysis is widely accepted as the primary approach for assessing adsorbent surface flaws (Jaishankar et al., 2014). This is because a larger absorbent surface area adds significantly to increased organic pollutant adsorption. BET analysis, which detects the pore structure of an absorbent such a mesosphere or microsphere, can also be used to determine the pore volume and porosity of an adsorbent. This has the added advantage of enabling for the investigation of pores (Nyika and Dinka, 2023). Palabıyık et al., (2019) demonstrated the potato peel waste as adsorbent used for treatment and cadmium removal with technique namely BET. The maximum removal efficiency was 76%.

4.2.3 Scanning electron microscopy

Scanning Electron Microscopy (SEM) is a frequently used method for characterizing materials. It enables the observation and analysis of the physical structure of bioadsorbents both before and after adsorption. This technique is valuable for simultaneously assessing the quantity and dimensions of pores, as well as confirming the substitution of a fibrous structure with a smooth one (Mosaddegh and Hassankhani, 2015). An enhanced technique is ultra-high-resolution scanning electron microscopy (SEM), which is well-suited for visualizing the surface texture of vegetables. This is achieved by scanning the vegetable with a high-energy electron beam that offers more sensitivity. Scanning electron microscope characterization techniques are used to determine the structure of an absorbent material (Warren-Vega et al., 2023). These approaches enable the observation of morphological changes that occur prior to and following adsorption reactions. They also provide an in-depth look at surface phenomena such swelling, aggregation, surface porosity, and molecular organization. SEM is occasionally used in conjunction with other tools to improve morphological traits (Chong et al., 2023). Scanning electron microscopy (SEM) is used in conjunction with energy dispersive X-ray analysis to detect and assess chemical synthesis or adsorption. The morphology of biosorbents changes as a result of numerous processes and the use of chemicals or activators. A scanning electron microscope (SEM) has substantially greater magnification power than an optical microscope, which has far lower magnification power (Sankhla et al., 2018; Chowdhary et al., 2020). Huang et al., (2023) depicted that cabbage peel waste prepared carbon material (PCC500) is a good absorbent material used by SEM and FTIR techniques for reducing pollution in industries.

The method is especially useful for identifying microstructural changes during processing and evaluating the efficacy of pretreatment techniques (Lee et al., 2009). Energy-dispersive X-ray spectroscopy (EDS) detectors can be added to SEM to provide simultaneous elemental analysis and composition mapping. Furthermore, SEM shows that various drying techniques have varied morphological results; spray drying, for instance, produces smaller, more homogeneous particles than freeze-drying or rotary evaporation. Because of this feature, SEM is essential for controlling product quality and improving processing parameters in waste valorization applications. SEM imaging offers a thorough picture of cellular structures, fiber patterns, and surface topography when used on vegetable and fruit waste (Vigneswaran et al., 2007). For example, discrete cells and intercellular gaps make up the well-organized cellular architecture seen in SEM micrographs of fresh apple tissue. On the other hand, severe structural degradation, such as cell wall breakage, decreased intercellular contact, and collapse of cellular architecture, is visible in SEM images of dried apple tissue (Thuwapanichayanan et al., 2011). Cell wall deformation, folding, and collapse are caused by temporary heat and moisture gradients during drying processes, which are responsible for these morphological alterations. SEM study of processed vegetable waste samples, such as pineapple waste that has been prepared with sodium hydroxide, clearly demonstrates surface texture changes and the breakdown of outer hemicellulose layers (Musa et al., 2021).

4.2.4 X-rays diffraction

X-rays diffraction (XRD) technique is widely used to observe a material's lattice structure. X-ray diffraction (XRD) techniques include the penetration of x-rays at various angles onto a sample, resulting in distinct patterns of diffracted peaks (Bhattacharjee et al., 2020). These peaks are indicative of the crystallinity of the material and its unit cell structure. Remarkably, the wide and small angle diffraction of the XRD pattern separates it into two separate patterns (Palabıyık et al., 2019). Wide-angle X-ray diffraction (WAXD) patterns created from transmission electron microscopy (TEM) pictures can be used to visualize the crystalline structure and unit cell of a material based on nanocomposite technology. The material's structure can be seen in small X-ray diffraction (SAXD) at a scale of 10 Å or greater (Nyika and Dinka, 2023).

4.2.5 Other methods

Vibrating-sample magnetometry method uses the vibration of magnetic materials that operate according to Faraday's Law where sensing coils detects the differences in voltage variation which is directly proportional to the sample's magnetic moment (Pundlik et al., 2021). There are numerous analytical techniques used to assess biomass-generated adsorbents, including TGA, XPS, UV-Vis spectroscopy, and elemental analyzers. TGA is a useful tool for testing whether or not adsorbents are stable when subjected to high temperatures. Through the use of XPS, surface composition and elemental chemistry can be determined (Thakur et al., 2022).

Beyond the limits of bulk analytical methods, XPS offers thorough elemental identification and chemical state information for vegetable waste products. Important information on surface oxidation states and the efficacy of chemical treatments is revealed by XPS analysis of materials formed from vegetable waste. Ion-beam sputtering may gradually dissolve material layers to reveal compositional differences with depth, making the technique especially useful for depth-profiling research (Ratner and Castner, 2009). The method is especially helpful for evaluating catalysts made from vegetable waste because it can identify and measure every element with the exception of hydrogen and helium.

Understanding catalytic properties requires knowledge of the local bonding environment, which is provided by the binding energy shifts (chemical shifts) seen in high-resolution XPS scans. These shifts indicate whether carbon exists as sp^2 hybridized aromatic carbon (C=C), carbon bonded to oxygen (C-O), or carboxyl carbon (C=O). For instance, XPS can measure the level of sulfonation in acid catalysts made from vegetable biomass or differentiate between various oxidation states of transition metals that might be added to waste-derived catalysts. This capacity is essential for comprehending catalytic interfaces and streamlining waste valorization procedures that rely on accurate surface chemistry. According to Smart et al., (2009), XPS results are commonly displayed as spectra that plot binding energy against photoelectron counts. Relative peak areas provide quantitative elemental composition information with an accuracy of 90–95% for key peaks XPS examination shows the oxidation states and bonding environments of important elements like carbon, oxygen, and sulfur when vegetable waste materials, including banana and citrus peels, are transformed into carbonized or sulfonated catalysts for biodiesel generation (Musa et al., 2021).

4.2.6 Relationships between functional groups and adsorption mechanisms.

The primary mechanisms for trapping the pollutants mainly heavy metals & synthetic dyes through use of vegetable derived biomass in waste water purification follows electrostatic interactions and complexation (Crini and Lichtfouse 2019). Vegetable wastes naturally contains cellulose, pectin, lignin and hemicellulose which are rich in oxygen-, nitrogen- and sulfur- bearing functional groups. These functional groups act as binding sites that grabs the dissolved toxic ions.

4.2.6.1 Molecular Breakdown:

There are chemical phenomena (electrostatic interactions and complexation i.e. chelation) that undergoes in the interaction based on the nature of the bond. **Electrostatic Interactions-** It depends upon the columbic attraction between opposing charges (Abdullah et al., 2019). Under optimal pH the hydrogen ions (H^+) is shed by functional group, leaving net negative charge on the surface of the adsorbent (Francesco et al., 2018) and heavy metal ions like Pb^{2+} , Cu^{2+}, dyes like Methylene Blue are drawn magnetically to these vacant sites having negative charge (Jayakumar and Vashishth 2026). **Complexation (Chelation)-** In this functional group i.e. Chelates or ligands donates its electrons to a metal ion which is positively charged and surrounds it tightly. **Electron Sharing:** On vacant d- orbitals of heavy metals is done by lone pairs of electrons on the atoms like oxygen, nitrogen and sulphur. **Ring Formation:** A ring like molecular structure (chelate) is formed on a single metal ion by multiple functional groups as they grab it and immobilize the pollutant (Martin et al., 2023).

4.2.6.2 Key functional groups involved

Carboxyl Groups (-COOH): It is found in pectin and organic acids & at moderate pH it easily deprotonate to $-COO^-$ which offers electrostatic targets for heavy metals (Li et al., 2019). Hydroxyl Groups (-OH): Present in agricultural waste having cellulose and polysaccharides. This group participates in hydrogen bonding. (Etale et al., 2023). Amino

Groups ($-NH_2$): It is present in residues of vegetable i.e. protein fragments where nitrogen is the electron donor for the coordinate covalent complexation (Sud et al., 2008). Sulfhydryl / Thiol Groups (-SH): In this sulphur atoms have an incredibly high chemical affinity for heavy metals, that ensures tight binding. **Ion exchange** – this mechanism relies upon the vegetable plant that have different biomolecules including cellulose, pectin, hemicellulose which contains different functional groups such as carboxyl, hydroxyl and amino acid. These groups release cations like Na^+ and Ca^{2+} and and replace it with Pb^{2+} and Cd^{2+} which are heavy metal contaminants in waste water (Ninduwezuo-Ehiobu 2026). Other one is π–π interactions and in this mechanism vegetable-based biosorbents especially vegetable/fruit peel are used for removing aromatic pollutants like dyes and pharmaceuticals from the waste water. In this mechanism there is overlapping of electron clouds b/w the biomass that is carbonised and the pollutant.

4.2.7 Comparative advantages/disadvantages of activation methods.

4.2.7.1 Waste water treatment through activation method.

There are two different activation methods i.e. Advanced oxidation processes and other one is secondary biological treatment (think activated sludge). The first one is related to kickstarting highly reactive species like hydroxyl radicals to break down pollutants. And the later one deals with the microorganisms that can chew through organic waste. Below some main techniques mentioning above methods are explained.

4.2.7.1.1 Advanced oxidation activation processes (Chemical and Physical)

In this process various oxidants are activated like hydrogen peroxide & persulfate, with the help of some external energy sources to break down the pollutants from the waste water (Worku et al., 2025). **UV Light Activation-** In this method we put UV light on H_2O_2 or O_3 and it splits into hydroxyl radicals, which destroys pollutants from waste water. (Yousaf et al., 2019). This method is having various superiority over other methods like it is good at breaking down various organic pollutants from waste water by killing pathogens at the same time. Also, chemical residue or extra sludge is not left behind in this method (Adam et al., 2010). Some disadvantages are also there like more consumption of electricity. This methods doesnot perform well if waste water is colored. Too much maintenance for UV lamps is required (Akgun & Unluturk, 2017). **Heterogeneous Photocatalysis (TiO_2 / MOF Activation)-** In this method light is used to wake up a solid catalyst, that creates electron-hole pairs that go on breaking the pollutants apart (Gregorio and Lichtfouse 2018). The main advantages of this method are that it can run with sunlight which is cost effective and breaks organics all the way down into CO_2 and H_2O. Also, the catalyst can be reused again as it holds well (Worku et al., 2025). The main disadvantage of this method is that the electron-hole pairs tend to recombine too fast that reduces its efficiency and the reactions are slow if dealing with the large volumes of industrial wastewater. **Fenton and Photo-Fenton Activation-** This method uses iron (Fe^{2+}) that chemically activates hydrogen peroxide. This method is extremely good to remove pollutants like textile dye from industrial wastes. No extra energy input or any high-pressure equipment is required. Some limitations of this methods are like it works only in narrow pH range of 2.8-3.5. Disposing of iron heavy sludge is quite expensive in this method. Also, this method needs constant H_2O_2 and iron catalyst which increases the cost (Sen et al., 2026).

4.2.7.1.2 Biological Activation Processes

These rely on activating microorganisms to eat up organic matter, whether it's suspended or dissolved in the water. **Activated Sludge Process (ASP)-** In this method constant aeration of water is done to activate and grow a greater number of anaerobic microbes that will feed on the waste. The main advantage of this method is that it removes the BOD very effectively and is congenial for big municipal plants. It is also very cheap to build initially per volume treated water. This method has limitations like running aeration constantly costs a lot over time and also produces tons of biological sludge that needs to be treated and stabilized (Worku et al., 2025). **Anaerobic Digestion / Activation-** This method involves activation of specialised bacteria under anaerobic conditions to break down heavy organic loads. The advantage of this method is that methane gas is produced that can be captured and used for green energy. Also, less sludge is produced then the aerobic methods and it handles concentrated industrial waste very well. The limitations of this method include slow running of system due to slow bacteria growth, sensitivity to fluctuating temperature and if not covered well smells very bad (Yeoh et al., 2022).

5. Wastewater treatment by using vegetable biowaste material

There have been numerous studies undertaken to study the possible applications of waste products obtained from vegetables for wastewater treatment. Furthermore, a variety of new composite materials including vegetable waste have been produced for specialized uses (Pathak et al., 2016). Vegetable waste comes in numerous forms, including peels, shells and hulls, pulp, stalk, seeds, bunch, and pomace, among others. These wastes come with a diversity of elemental compositions, as well as inherent structures and morphologies, which eventually have an impact on the outcome (Ince et al., 2017). Furthermore, among the various adsorbents that are formed from vegetable waste, the vegetable waste peels are considered to be potential vegetable waste sources for the production of bio adsorbents. This is due to their high lignocellulosic content, which makes it easier to generate a high carbon elemental composition (De Gisi et al., 2016). Furthermore, it has been observed that using peels as absorbents can help with the heavy metal adsorption process. Peels include polar-organic compounds, which result in the formation of chelates with metal ions (Jain et al., 2016). Table 2 depicted the different vegetable-based wastes are used for wastewater treatment.

5.1 Vegetable peel-based

The peel of a vegetable is the outermost protective layer, also known as the skin or rind, and it contains a wide variety of organic chemicals, including carbonyl, phenolic, and carboxyl. Peels are thought to aid in the adsorption of heavy metals because they contain polar-organic chemicals that can assist the formation of chelates with metal ions (Wadhwa et al., 2016). This is because peels contain methyl groups. Vegetable peels and skins are a natural, environmentally friendly, and cost-effective source of adsorbents that may eliminate many types of water impurities and minimize pollution. As a result, they are a resource that is renewable and has a lot of potential. Peels from vegetables have the distinct feature of being able to be used as an edible coating (Nathan et al., 2022). Edible coatings are made of extremely thin layers that are applied to the food's surface to increase its shelf life, maintain its functional aspects, and do it for the least amount of cost per serving (Chettri et al., 2023). The development of a modified atmosphere is another way that coatings help to modify minimally processed and fresh food in a number of ways, such as sensory quality, antioxidant qualities, color, firmness, ethylene production, microbial growth inhibition, and organic compounds under anaerobic processes (Chettri et al., 2023; Shafi et al., 2023). There's enough cellulose, starch, hemicellulose, and fermentable sugars in the potato skin. The films with lower potato peel concentrations produced a higher water vapour pressure than the films with higher potato peel concentrations in the biopolymer membrane (Mahajan and Jaspal, 2022).

This was possible because the film matrix had a larger pore size, despite the fact that it had a denser structure. The biopolymer film covering made from potato peels proven to be useful in the process of producing biodegradable food packaging that has a higher value for commercial application (Nathan et al., 2022). Choumane et al., (2021) evaluated the potato peel-based bioflocculant in wastewater treatment. The findings demonstrated that the utilization of a flocculant derived from natural potato peels, in conjunction with a coagulant, offers a highly efficient and eco-friendly method for treating wastewater through coagulation. Akkaya and Güzel, (2013) studied the cucumber peel based biosorbent for copper and lead removal for wastewater treatment. The maximum amount of Cu (II) ions that may be absorbed per gram of biosorbent is 88.50 mg/g, while for Pb (II) ions it is 147.06 mg/g.

5.2 Vegetable composite hull-based adsorbed

The hull is the rigid outer covering of seeds or grains that provides protection during the germination process. Hulls are typically removed prior to boiling or manufacturing due to their firm texture (Massironi et al., 2023). On a global scale, hulls are a significant contributor to food waste, particularly rice hulls, as rice is heavily consumed in Asian countries. The solid structure of vegetable shells and hulls makes them effective adsorbent materials, contributing to their long lifespan as adsorbents (Shrivastava and Singh, 2022).

5.3 Vegetable seeds

Vegetable seeds, in addition to other portions of vegetables, have also been utilized in the process of purifying water that has been contaminated. Some of the by-products that are produced by vegetables include the seed coat, which is the outermost coating that covers the seeds or beans and serves the purpose of protecting them from damage from the environment (Jones, 2019). Lignin is a source that can supply adsorbent materials with a carbon range of 45–50%, and it has been observed that vegetable seeds have a high concentration of lignin from sources. The texture and flavor of seed coats are often not edible, with the exception of certain thin seed coats, such as peanut seed coats. Seed coats are not ingested (Mahajan and Jaspal, 2022). Kowalkowska and Jóźwiak, (2019) depicted the usage of pumpkin seeds as biosorbent for removing dyes and treating wastewater. The sorption capacity varies from 96.01 to 163.39 mg g^{-1}.

5.4 Other vegetable waste component adsorbents

Various other components of vegetable waste, including stems, leaves, pulp, bunches, pomace, etc., have also been used to create biosorbents for treating wastewater. Banana peel waste, which is high in cellulose and starch, may be effectively transformed into sustainable, biodegradable plastics, providing a green substitute for petroleumbased, non-biodegradable packaging, according to Lakkimsetty et al., (2025). Using Syzygium cumini L. (Jamun) leaves as an inexpensive adsorbent, King et al., (2008) investigated the biosorption of zinc from aqueous solutions. Maximum metal uptake was found to occur around pH 5.0, with equilibrium aligning well with the Langmuir isotherm and kinetics following pseudo-second-order models.

Namdeti et al., (2025) looked at the removal of lead (Pb) and zinc (Zn) from aqueous solutions using powdered Prosopis cineraria leaves as an inexpensive adsorbent. Response Surface Methodology (RSM) optimization, isotherm modeling, and batch adsorption tests were used in the study. Kalpana et al., (2016) looked at the use of activated carbon made from Anthocephalus cadamba (ACAC) to remove methylene blue (MB) dye from aqueous solutions. The study confirmed ACAC as an efficient low-cost adsorbent for wastewater treatment by optimizing adsorption parameters using Response Surface Methodology (RSM).

6. Parametric evaluation

The data for biosorption through vegetable waste adsorbents is evaluated against the Langmuir and Freundlich isotherm models, alongside pseudo-first, pseudo-second order kinetic models for understanding how adsorption takes place rather than just its occurrence. In Langmuir model fixed number of uniform binding sites are assumed which are energetically identical that indicates in advance a maximum adsorption capacity (q max), which is not in the case of Freundlich isotherm models as it assumes a heterogenous surface with no defined saturation limit (Mozaffari et al., 2021). The adsorption data in various vegetable waste biosorbent studies reviewed here fits the Langmuir model better than the Freundlich model as the adsorption occurs at specific, consistent with the different but limited functional groups (-OH, -COOH) which are prevalent on peel derived biomass with q max values ranging from 4 to 5.35 mg/g. On the other hand, the pseudo-second order models dominate pseudo first order in context to the studies reviewed here, which suggests that chemosorption where there is chemical interaction between the contaminant and the biosorbent surface group is the rate limiting step instead of physical attachment. This can be taken together as a shared mechanism for Langmuir model dominant isotherm behaviour and pseudo second order kinetics, where the chemical bonding at discrete functional group rich sites governs uptake (Essien et al., 2025).

6.1 Effect of pH

The pH of a solution is of great importance in an adsorption system due to the alteration of surface characteristics of both the adsorbent and adsorbate at different pH levels. The investigation on phenol adsorption using chemically activated potato peels found that as the solution pH increased from 1 to 8, the removal percentage of phenol decreased due to the higher concentration of OH- ions at higher pH levels (Kaçakgil and Çetintaş, 2021). The increasing concentration of hydroxyl ions in the solution interrupts the diffusion of phenol ions, lowering the adsorption capability. The pH of the solution has a significant impact on the relationship between the existence of functional groups on the cell surface and the presence of cationic species (Fakhri et al., 2023). The biosorption capability is minimal at low pH and reaches its maximum with increasing pH. Metals undergo precipitation at elevated pH levels as a result of the production of hydroxide ions (OH-). Under acidic conditions, the cell wall ligands have a strong affinity for hydronium ions, which leads to a decrease in the uptake of Mn^+ ions due to the competition between H_3O^+ and Mn^+. With an elevation in pH, an elevated number of ligands, including carboxyl, phosphate, imidazole, and amino groups, are present (Dey et al., 2018). These ligands possess negative charges that enable them to absorb Mn^+ ions, which are then adsorbed onto the surface of the cell. It has been shown that as the solution pH drops, copper mobility and stability increase. As the pH rises, chromium's oxidation state changes from more stable Cr(III) to more hazardous Cr(IV). For lead, higher pH levels cause immobilization due to the formation of precipitates, whereas lower pH levels increase the concentration of free lead (Kasbaji et al., 2023). Increasing the pH results in the adsorbent surface gaining a negative charge due to metal adsorption. This, in turn, promotes the sorption of heavy metal ions that carry a positive charge. The majority of metals exhibit decreased rates of adsorption at pH levels below 3, but at higher pH levels, the concentration of H^+ ions fall, resulting in an increase in accessible sorption sites (Kaçakgil and Çetintaş, 2021). The *Brassica Comptris* is utilized as a biosorbent for the purpose of eliminating harmful metals. Through experimentation, it was shown that the most favourable pH for the most absorption of Ni (II) and Cr (VI) ions is pH 9, while for Pb^{2+} it is pH 4 (Jagadeeswara Reddy et al., 2021).

6.2 Effect of temperature

In a biosorption process, temperature influences both the rate and quantity of adsorption. The adsorption capacity decreases as the temperature rises due to the decreased stability of the adsorbent metal ion complex. The rate of adsorption increases proportionally with temperature (Tamjidi and Ameri, 2020). The diffusion rate of adsorbent molecules increases when temperature rises in both the outer boundary layer and the adsorbent pores. This could potentially diminish the solution's viscosity. The temperature must remain below a threshold that could potentially result in detrimental physical or chemical effects on the adsorbent material (Abdallah, 2013). The temperature plays an important role in deciding whether the adsorption process is endothermic (absorbing heat) or exothermic (releasing heat). Adsorption treatment methods typically exhibit endothermic behavior (Kaçakgil and Çetintaş, 2021). The biosorbent's sorption capability increases as temperature rises. The growth of active sites on the adsorbent's surface or the migration of pollutant molecules could both account for the rise in sorption capacity. Increased warmth causes the sorbent's internal structure to expand, allowing dye molecules to penetrate even deeper (Bilal et al., 2021).

6.3 Effect of biosorbent dose

The increased adsorption capacity with more adsorbent is due to the increasing availability of vacant sites on the adsorbent for the adsorbate in solution. The amount of absorbent used has a considerable influence on the extent of biosorption. The amount of adsorbent used directly corresponds with adsorption effectiveness because it gives more accessible adsorption sites (Gopakumar et al., 2018). As a result of the constant presence of metal ions in the solution, the adsorbent's adsorption capacity per unit mass decreases. Increasing the amount of adsorbent causes a decrease in adsorption per unit mass of adsorbent. This occurs because the contaminant is insufficient to completely cover the adsorbent's exchange sites (Abdallah, 2013). Furthermore, changing the adsorbent's dose increases its surface area. Furthermore, a greater adsorbent dose may result in the desorption of adsorbed ions from the adsorbent's surface as a result of contact with the ions in the solution. Hence, the optimal amount of adsorbent is crucial for efficient elimination of pollutants (Jagadeeswara Reddy et al., 2021).

6.4 Effect of adsorbent size

The most essential characteristics of the adsorbent are its surface area and its size. The adsorbent's surface area is also highly important. Adsorbents are often spherical or irregular in shape, and their surface is typically covered with huge pores. When the size of the adsorbent particles is smaller, their grains are closer to the spherical shape. This means that they have more interaction with the fluid phase, which in turn speeds up the adsorption process (Fakhri et al., 2023). Generally, the adsorption rate falls as the particle size of the adsorbent lowers. This is because the adsorbent contact surface with the adsorbent material increases if the particle size reduces. For certain types of adsorbents, the fact that the size of the adsorbent does not have any impact on the adsorption process is an essential fact (Dey et al., 2018). If, on the other hand, the size of the biosorbent is tiny, it is suitable for the batch process. This is because the adsorbent has a high surface area, which makes it suitable for the batch process. However, it is not suited for the column process because of its poor mechanical strength and the fact that it causes column coagulation (Jones et al., 2019). Table 3 depicts the effects of particle size on adsorption. The physical alterations that adsorbents undergo play a unique role in altering their sorption capacity. The quantity of surface area accessible for adsorption is determined by the particle size distribution (Bahadir et al., 2023). Adsorbents with smaller particle sizes have higher sorption capacities because they have more active vacant sites and a bigger surface area. The adsorbents' surface pores and holes enlarge as a result of the increased surface area (Figueira et al., 2022).

6.5 Effect of initial concentration of pollutants

The amount of contamination that is absorbed per unit mass of adsorbent increases with the initial contamination concentration. Nevertheless, when the starting concentration of the contamination rises, the efficacy of removing the pollutant (expressed as the percentage of adsorption) declines. It was discovered that when the starting concentrations increase, the percentage of metal removal falls due to a decrease in the availability of adsorption sites on the surface of the adsorbent (Monlau et al., 2015). At lower concentrations, metals are attracted and attached to specific areas that are easily reachable, however at higher metal concentrations, fewer potential sites are occupied. Moreover, it was found that the adsorption of metal ions and the achievement of equilibrium increase proportionately with the rise in metal ion concentration from 20 to 120 mg/L (Pathak et al., 2016). Additionally, any mass movement between the liquid and solid phases raises the potential interaction between biomass and metal ions, which increases the amount of metal ions that are adsorbed (Tamjidi and Ameri, 2020). Table 4 depicts the relationship of adsorption concentration with that of various parameters that withhold the adsorption potential.

6.6 Effect of contact time

The length of contact is an important aspect in the biosorption process. As the contact duration between the adsorbent and the contaminant increases, so does the rate of adsorption due to improved interaction between the two. The crucial aspect is that as the contact duration increases, the level of adsorption reaches a plateau and remains relatively unchanged (Ossai et al., 2023). Furthermore, it is cost-effective to ascertain the duration of contact, in addition to the level of absorption. The appropriate contact time for adsorption of heavy metals varies depending on the adsorbent composition and the specific pollutant being targeted. A study revealed that initially, the % clearance rate of Pb and As was higher. This phenomenon is probably brought about by the early adsorption process's initial abundance of adsorbent surface area; but, as the process progresses, fewer sites on the biosorbent become available, which lowers the rate of adsorption (Saravanan et al., 2023). The maximum proportion of Pb and As that can be removed within a 60-minute timeframe. Another investigation revealed that the rate of Cu2+ absorption, expressed as a percentage of length, was rapid and metaphorical within the initial five-minute period. The initial five minutes were fully accomplished (92%) and subsequently diminished progressively as the call duration increased. The first quick adsorption occurs as a result of surface desorption, while the subsequent gradual adsorption is attributed to the transfer of metal ion membranes into the cell cytoplasm, sluggish intracellular diffusion, or reduced permeability of the cell wall (Kasbaji et al., 2023).

7. Vegetable waste-derived material vs other available components

Since the active sites on the adsorbent's surface are limited in number, so the efficiency of contaminant removal decreases as number of solutes involved in the adsorption process. If more than one pollutant reduces another through their presence, the interaction is known to be as an antagonistic. Conversely, synergistic interaction involves multiple ions presence targeting the enhanced adsorption of a specific target pollutant. Moreover, there is strong influence on competitive adsorption by temperature, reliable pH and concentration factor of contaminants (Sulaymon et al., 2013; Yin et al., 2024)

The promotion of green chemistry and sustainable technologies has been greatly aided by the use of biomass-generated adsorbents in a variety of applications. Waste biomasses is a main source of the biosorbents (Tokay and Akpınar, 2021). In addition to reducing solid waste, using waste biomass as an adsorbent provides a sustainable way to remove dangerous water pollutants. To create an effective adsorption system for water purification, it is crucial to tune the process parameters, including the initial concentration of pollutants, temperature, pressure, and solution pH, to achieve the highest possible removal of contaminants (Karić et al., 2022). Adsorption is a highly effective technique for removing dyes from wastewater. By substituting low-cost biosorbents for commercial adsorbents, this method offers a cost-effective solution that achieves near-complete dye removal. As a result, methylene blue is better adsorbed onto a potato peel bioadsorbent than it is onto commercial activated carbon or other pricy adsorbents (Bahadir et al., 2023). The powdered stems and leaves of the potato plant are employed as an absorbent to eliminate methylene blue and malachite green dyes from water-based solutions. The leaf powder demonstrated superior adsorption capabilities compared to the stem powder for both dyes (Syeda et al., 2022). Therefore, the rough texture and chemical groups included in potato waste make it a highly suitable option for clean-up purposes. To extract Cr (III) and Cr (VI) from liquid solutions, carrot waste biomass is used. A maximum absorption of 86.65 mg/g of Cr (III) was observed in the waste biomass at pH 1, which was its maximal capacity. The highest absorption capacity of Cr (VI) at pH 5 was observed to be 88.27 mg/g. A biosorbent size of 0.250 mm, an initial concentration of 100 mg/L, a temperature of 30°C, a contact length of 240 minutes, and an ideal biosorbent dose of 0.1 g were found to yield the maximum levels of adsorption (Bahadir et al., 2023; Figueira et al., 2022). Acetone was hypothesized to eliminate the protein and lipid components of the waste biomass surface, so revealing additional metal binding sites to enhance the process of adsorption. An assessment was conducted to determine the efficacy of garlic peel in removing methylene blue from a water-based solution using a batch approach (Chen et al., 2021).

Desorption is the term used to describe the process by which pollutants and the adsorbent surface form a chemical or physical link that regenerates the biosorbent. For improved recovery, it concentrates the pollutant in addition to regenerating it. Sulfuric acid, nitric acid, and hydrochloric acid are common desorbing agents for cationic heavy metals. Calcium chloride and sodium hydroxide are used for organic contaminants. There have been reports of heavy metal recovery rates of up to 80% using the acidic solutions. Additionally, the use of treated biosorbents results in more than five consecutive cycles of adsorption and desorption. Inadequate regeneration and treatment of wasted biosorbents result in significant organic matter breakdown, contaminants seeping into the environment, and a gradual decline in treatment effectiveness (Saadi et al., 2025; Hamad and Idrus, 2022). Higher ionic strength prevented the ions from congregating around the biosorbent surface, which ultimately reduced the attraction between the target matter ion and the biosorbent. Additionally, the coexisting ions (sulfate and carboxyl groups) cause a competitive adsorption process. Additionally, equilibrium uptake decreases, which has a negative effect on biochemical kinetics (Aranda-García et al., 2020).

The highest amount of adsorption that a monolayer can hold was determined to be 142.86 mg/g at a temperature of 50°C. The efficacy of Okra waste from food canning procedures in adsorbing Pb (II) from aqueous solutions was examined. The results demonstrated a 99% removal of Pb (II) within the ideal pH range of 4-6. The process of adsorption in this context encompasses either ion exchange or the creation of hydroxyl complexes (Bayuo, 2021). The removal of methylene blue has been slightly more efficient with diethylenetriamine-modified hollow polymer particles (HPP-DETA) and AQSOA-Z05 Zeolite hydrogel composites, but their preparation and material costs are prohibitively high overall, so they are unlikely to be widely used in commercial applications (Tsade et al., 2020). The development of a sustainable strategy for handling vegetable waste has become crucial in the current context. Therefore, a solution that can fully utilize these waste materials' potential and help achieve the social, environmental, and economic benefits obtained from them must be developed. Furthermore, using vegetable waste especially peels to produce value-added goods like edible films, probiotics, nanoparticles, carbon dots, biochar, and biosorbents can be a sustainable and eco-friendly way to expand your business and repurpose this waste for useful products (Karić et al., 2022). Many of these interventions are still in their early stages and lack the technology advancements and discoveries. Therefore, it is imperative to establish collaborations between researchers and industrialists in order to enhance the economic viability of these valuable horticulture byproducts, with the assistance of an initial investment. Furthermore, it will facilitate the utilization of horticulture waste for the production of high-value goods (Syeda et al., 2022). Table 5 depicts the comparative analysis of biosorbent performance in water purification.

8. Future Aspects and Challenges

The application of vegetable waste following chemical or physical activation offers a sustainable approach to managing solid waste and replacing expensive commercial adsorbents. Due to the higher concentration of hemicellulose and lignin, as well as their comparatively inexpensive cost, there has been considerable interest in using them as adsorbents in recent years (Ganesh et al., 2022). Before vegetable wastes can be used as adsorbents, they are thoroughly examined to determine their properties, including porosity, specific surface area, and adsorption rate for certain contaminants. The expense of chemicals for the manufacturing and regeneration of vegetable waste generated biosorbent is a significant concern in its development (Aguilar-Rosero et al., 2022). Hence, the overall production cost can be diminished by integrating acids and alkalis with physical methods in the production of adsorbents from vegetable waste. However, it is necessary to develop sustainable, and environmentally acceptable techniques to modify biosorbents derived from vegetable waste. These modifications should result in adsorbents that have high adsorption capacity and strong physio-chemical properties, making them suitable for use in industrial applications (Yadav et al., 2020). When vegetables are out of season, they tend to be costly. During times of low demand, the cost of raw materials will fluctuate. These vegetable waste-derived bioactive compounds can be effectively preserved for extended periods during harvest. To safeguard against microbial contaminations, the biosorbents can be stored in plastic bags after drying. Further exploration should be conducted to address the energy-intensive nature of the quick drying process for biosorbents (Tokay and Akpınar, 2021; Patel, 2012). The adsorption of specific contaminants is an additional difficulty for waste vegetable-based adsorbents. This necessitates the use of experimental techniques aimed at designing homogenous and selective chemical agents. Similar to traditional activated carbon materials, biosorbents generated from vegetable waste can exhibit inadequate chemical bonding, resulting in structural instability and limited ability to remove pollutants with low adsorption rates (Sahu et al., 2022). Hence, it is essential to establish a suitable interaction between biosorbents formed from vegetable waste and chemical modifiers. This interaction should enable a chemical bonding process that effectively captures and immobilizes ionic contaminants within the inner layer of the adsorbents. Acid activation can occasionally cause corrosion, although certain investigations have shown that pollutants can be adsorbed without the need for chemical activation (Tsade et al., 2020). This alternative strategy may be both cost-effective and environmentally friendly. In this regard, it is possible to increase the physical activation parameters and so avoid the need for chemical activation which is expensive because it requires the use of chemical modifiers. The high expense of using biosorbents in large-scale applications poses a barrier to their use in industrial applications (Nyika and Dinka, 2023). Other limitations which prevent its industrial implementations include few reasons like in most of the lab studies where vegetable waste biosorbent is used under controlled conditions the waste water which is used is generally a single contaminant solution. Whereas, in case of real waste water there are different competing ions, fluctuating pH, varying temperature and a mixture of pollutants that all will compete for the same binding sites on the adsorbent surface leading to differ in its performance as compared with a single contaminant solution in lab. Also, vegetable waste isn't a standardised industrial input as it always varies depending on the season, growing conditions and the maturity stage of the produce. Other things like the expenses involved include material costs, which encompass the cost of raw materials, synthesis costs, transportation costs for raw materials and adsorbents, storage costs, chemical costs, personnel costs. The operational cost of the adsorption process encompasses expenses related to process materials, energy consumption, personnel, maintenance, and other associated costs. On the other hand, the capital cost comprises expenses related to land, overall infrastructure, process machinery and equipment, installation, and other relevant factors (Chanda et al., 2024). Regenerating biosorbents for heavy metal removal can be challenging and expensive, may involve on-site disposal of the adsorbents. For the removal of organic contaminants and toxins, biosorbents are better choice. Techno-economic analyses and feasibility studies for the treatment of various wastewater sources using a variety of biosorbents must be conducted to support laboratory or small-scale research (Bobde et al., 2021).

Vegetable growth exhibits regional variations worldwide due to diverse weather conditions. However, the successful cultivation of vegetables and food crops through optimum forestation requires meticulous attention to land requirements, effective policy implementation, stakeholder's approval, and proficient management. The high expense of using biosorbents on a large scale is a barrier to its implementation in industrial applications (Jaishankar et al., 2014). The expenses involved include material costs, which encompass the cost of raw materials, synthesis, transportation of raw materials and adsorbents, storage costs, chemical costs, and personnel costs. The operational cost of the adsorption process includes expenses related to process materials, energy consumption, personnel, maintenance, and other associated costs (Aguilar-Rosero et al., 2022). The capital cost encompasses several components such as land, infrastructure, process machinery, equipment, and installation expenses. Regenerating biosorbents for heavy metal removal can be a challenging and expensive, and there is a risk of on-site disposal. However, biosorbents appear to be a more favourable option for eliminating organic pollutants and poisons. To enable laboratory or small-scale research, techno-economic analyses and feasibility studies for the treatment of different wastewater sources using different biosorbents must be conducted (Singh et al., 2021; Yadav et al., 2020). The physical processing also faces challenges with the techniques like steam activation, CO_2 activation or microwave assisted synthesis works well in small reactors inside a lab but when we move from grams to tonnes it requires reactors with different design, and quality control system. Lack of data where proper feasibility study comparison with the full life cycle cost of vegetable waste biosorbents has been done at an industrial scale makes it hard for the industry to shift from promising lab material to actual investment in this. Adsorption capacities, operating conditions, and limitations of different vegetable-waste-based adsorbents are summarised in Table 6. Also, other major wastewater pollutants are listed in Table 7.

9. Conclusion

A paradigm change in sustainable wastewater treatment is represented by vegetable waste-derived biosorbents, which simultaneously address the growing issue of agricultural and food processing waste and the global problem of water contamination. This thorough analysis shows that vegetable waste materials, such as peels, leaves, seeds, and stems, have significant potential as affordable substitutes for synthetic adsorbents and commercial activated carbon. These biosorbents demonstrate that efficacy and sustainability are not mutually exclusive, with removal efficiencies reaching 95–99% for a variety of contaminants, including heavy metals, dyes, and emerging pollutants. Vegetable waste biosorbents provide several main advantages over synthetic alternatives, including low processing costs, the use of plentiful raw materials, benefits to the circular economy through waste valorization, and a substantial reduction in environmental impacts. Due to their natural functional groups, including hydroxyl, carboxyl, amino, and sulfhydryl moieties, materials like potato peels, carrot waste, garlic peels, and okra biomass exhibit remarkable adsorption capabilities ranging from 86.65 to 142.86 mg/g. Additionally, several United Nations Sustainable Development Goals are directly supported by these adsorbents, including SDGs 6, 12, and 13. However, addressing important issues, including cost optimization, standardization of synthesis techniques, regeneration procedures, and regulatory frameworks, is necessary to scale vegetable waste adsorbents to industrial uses. Collaboration between researchers and industry is crucial to overcoming financial obstacles and creating commercially successful technologies. The shift from laboratory-scale research to full-scale implementation will be accelerated by investments in enhanced characterisation techniques and techno-economic feasibility studies. Conclusively, vegetable waste biosorbents are essential tools for achieving SDGs because they offer a promising route toward affordable, environmentally friendly water treatment solutions that concurrently support global food security and environmental preservation.

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Table 1. Proximate and elemental analysis of different vegetable and their waste volume

		Proximate composition	**Elemental composition**	**Lignocellulosic composition**	**Wast e**	

Vegetable	Waste	Moisture (%)	Volatiles	Ash (%)	C	H	O	N	Cellulose	Hemicellulose	Lignin	volume (Million metric tons)	References
Pumpkin	Peel	71.44	84.4	7.1	139	-	18	150	41-49	24-29	9-26	22.9	Akpasi et al., 2023; El-Hadary, 2023
Cassava	Peel	9.93-1146	8.54	4.36	82.97	70.2	29.87	5.81	14.17	23.40	10.88	350	Matovu et al., 2022
Water melon	Peel	8.19	85.36	6.18	39.69	6.23	51.52	2.23	58	14	11	42	Sadiq et al., 2021
Jackfruit	Leaves	-	63	19	37.5	4.9	37.8	0.7	34	4	19	-	Amadi et al., 2018
Potato	Peel	11.2	56	7.56	0.12	48	-	60	30	14	0.22	20	Vaitkevičienė, 2019
Cucumber	Peel	97	78	11.6	1.00	-	3.00	39.3	18.22	6.7	4.51	20-30	Niyi et al., 2019
Tomatoes	Peel	92.58	38	8.75	1.8	4.1	14	0.2	8.60	25	5.85	4.3-10.2	Elbadrawy and Sello, 2016
Carrot	Peel	86	31	5.5	11	2.7	-	50	80	9.14	2.48	1.3	Nguyen and Le, 2018
Onion	Peel	70	77.70	5.50	0.05	-	5.00	1.7	41-50	16-26	26-39	5.5	Oguezi et al., 2019

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Garlic	Peel	65	85	5.0	6	10	1.0	-	41.7	8	25	3.0	Yusuf et al., 2018
Cabbage	Leaves	90.2	75	1.32	0.23	45	20	-	37	4.46	-	50	Tayyeb et al., 2017
Carrot	**Pomace**	2.5		5.5	301				71.6 ±	55.8			Surabhi et al.2018

Table 2. Utilization of different vegetable biowaste used for wastewater treatment

Vegetable	Part of vegetable	Adsorbate	Adsorption Capacity (qm) in mg/g	Value	Dose	Ph	References
Artocarpus nobilis	Peel	Ni (II)2+	0.012 mg/g	Ion exchange		pH of 4	Priyantha and Kotabewatta, **2019**
Blepharispermum hirtum	Fruit shell	Zn(II)	27.66 mg/g		0.5 g/L	6.0,	Namdeti et al. 2023
Bottle gourd	Peel	Copper, Silver and Iron	Adsorbed 99% copper, 95% silver and iron	Used for waste water treatment and have nutritional importance			Ahmed et al., 2018
Bottle Gourd	Shell	Pb(II), Cd(II), Zn(II), Cu(II), Ni(II)	425 mg/g	Upto 90 percent efficiency Used to remove heavy metals, oils and dye	0.5 g/L	7.2.	Nikolić et al. 2024

				from natural or wastewaters			
***Calabrese* broccoli**	stalks	Pb(II)	586.7 mg g^{-1}	88.3 percent sorption at		pH 4.8	Granado-Castro et al. 2024
Carrot (Residue)		Cr(III), Cu (II), Zn(II)	1.65 1.82 1.45	Initial ion concentration of 20 to 500 mg/L None Ion exchange		pH of 4	Nasernejad **2005**
Carrot	Peel	Nickel (II) ion	1000	Presence of bioactive compounds			Changmai et al., 2018
Cassava	Husk	Copper (II)	0.14	Used as biosorbent and have active compounds			Jorgetto et al; 2014
Chinese Cabbage	Leafy part	Phosphate	127.2	Presence of polyphenols , Used as biosorbent			Alni et al., 2019
Cucumber	Peel	Lead (II) ion	133.6	Bioactive substances possessing antioxidant properties			Singh et al., 2021
Cucumber	Peel	Methylene blue	A dosage of 4 g/L adsorbed 81.4%	Have bioactive compounds and used as biosorbent			Shakoor and Nasar, 2017

			methylene blue				
Cucumber	peel	As (V), Cd (II), Cr (VI), Cu (II), Hg (II), Pb (II) and Ni (II)	17-84 percent efficiency	Cost-effective	0.1 mgL^{-1}	6.5, to 8.5	Nathan et al. 2022
Garlic	Peel	Methylene blue	Adsorbed 142.86 mg/g of methylene blue	Nutritional value and have active compounds			Hameed and Ahmad, 2009
Green Vegetables	Green leafs	Copper (II) ion	75.0	Used for wastewater treatment, Important bioactive component			Patel, 2012
Musk Melon	Peel	Cd (II), Cu(II), Pb(II)	45.4 33.1 143.3 mg g^{-1}			pH of 5–7	Tran et al. 2008
Onion	Peel	Cadmium (II) ion	21.28	Flavouring agent, Nutritional supplement			Shaikhiev et al., 2022
Pea	Pods shell	As(V)	99.7%	As adsorption and reusability of biosorbents.	0.5 mg/L	Alkaline	Sahu et al. 2022
Pea	Haulm	Methylene Blue	167 mg/g	Water treatment	0.5 g/L	Acidic to	Hollidayy et al. 2024

						alakaline	
Potato	Peel	Cu(II)	0.15	Surface complexation and ion exchange Initial ion concentration of 150 mg/L Particle size of 0.2 mm		pH of 6	Aman et al. 2008
Potato	Shell	Cu(II),	90 41.7	Electrostatic interaction		6.8	Feizi and Jalali 2015
Potato	Peel	Cadmium (II) ion	80.52	Presence of bioactive compounds and used as biosorbent			Foroutan et al., 2023
Potato	Peel	Ni (II) ion	1000	Presence of bioactive compounds			Hoseinzadeh et al., 2014
Potato	peel	As (V), Cd (II), Cr (VI), Cu (II), Hg (II), Pb (II) and Ni (II)	17-84 percent efficiency	Cost-effective	0.1 mgL^{-1}	6.5, to 8.5	Nathan et al. 2022
Potato, Carrot	Peel	Nickel	A dosage of 3.0 g	Nutritional value and			Gill et al., 2013

			adsorbed 79.32% of nickel	have polyphenols			
Pumpkin	Seeds	Copper (II) ion, Silver and Nickel	13.85	Used as biosorbent and have nutritional value			AntimaKatiyar and Sharma, 2014
Rapeseed	Leafy part	Phosphate	132.8	Nutraceutical value and have active compounds			Morosanu et al., 2020
Rapeseed	Meal	Cr(VI), Cd(II), Cu(II), Pb(II), Ni(II) and Zn(II)	40-80 percent efficency	agricultural byproducts with zero waste	0.15g/30 ml	PH 2.0	Liu et al 2023
Sponge gourd	Peel	Malachite green	A dosage of 8 g/L adsorbed 69.64 mg/g of malachite green	Have antioxidants , active compounds and used as biosorbent			Ng et al., 2016
Tomato	Stem	Direct Orange 46	4.24 mg g^{-1}	Upto 99 percent phosphate and DO 46 removal potential	2g/L	pH = 6.0	Eskikaya et al. 2023
Waste hop (*Humulus Lupulus*)	**Stems**	Malachite green, methylene blue, and	398.9, 209.8, and 133.2 mg g^{-1}	98.4% (MG), 98.8%, (MB)and 98.5% (CV) removal	2 g/L;	8.0 Alkaline	Perendija et al. 2024

		crystal violet		efficiency from wastewater			
Watermelon	Peel	Cu (II)	1.39	Utilized as biosorbent			Muhammad et al., 2020
Ginger	Peel	Zn, Cr, Cd, Pb and Ni	10.65, 0.10, 0.50, 15.05, 0.10 mg kg^{-1}	Heavy metals from crude oil polluted soil	*100g /L*		

Table 3: Particle size effects on adsorption

Parameter	**Large Particles**	**Small Particles**	**Key Impact**
Surface Area	Lower	Higher	↑ Small size = ↑ Capacity
Fluid Contact	Limited	Extensive	↓ Size = ↑ Interaction
Adsorption Rate	Slow	Fast	↓ Size = ↑ Speed
Mechanical Strength	Good	Poor	↓ Size = ↓ Durability
Column Compatibility	Suitable	Not Suitable	Large better for column process
Batch Process	Moderate	Excellent	Small better for batch process

Table 4: Adsorption concentration and relationship with various parameters

Parameter	**Relationship with Initial Concentration**	**Evidence**	**Reference**
Amount Adsorbed per Unit Mass	↑ Increases	From 12.5 to 48.6 mg/g (20→120 mg/L)	Pathak et al., 2016
Removal Efficiency (%)	↓ Decreases	From 92% to 56% (20→120 mg/L)	Monlau et al., 2015
Available Adsorption Sites	↓ Decreases	Sites become saturated at higher concentrations	Monlau et al., 2015
Fluid-Solid Interaction	↑ Increases	Enhanced mass transfer improves adsorption	Tamjidi & Ameri, 2020

Table 5: Comparative analysis of biosorbent performance in water purification

Adsorbent Material	Type (Bio/Commercial)	Target Pollutant	Max Adsorption Capacity	Optimal Conditions	Removal Efficiency (%)	Cost Comparison	Key Advantages
Potato Peel (Powder)	Biosorbent	Methylene Blue	Superior to AC	Room temp	Near Full	Very Low	High accessibility, rough texture, low cost
Potato Leaf Powder	Biosorbent	Methylene Blue & Malachite Green	Superior	Room temp	95+	Very Low	Better than stem powder, chemical groups aid binding
Potato Stem Powder	Biosorbent	Methylene Blue & Malachite Green	Good	Room temp	85-90	Very Low	Lower capacity than leaf powder
Commercial Activated Carbon	Commercial	Methylene Blue	Standard	Room temp	85-90	High	Established material, industrial standard
Carrot Waste Biomass	Biosorbent	Cr(III)	86.65 mg/g	pH 1, 30°C, 240 min	95+	Very Low	Cr(III) specific, acetone pretreatment enhances binding
Carrot Waste Biomass	Biosorbent	Cr(VI)	88.27 mg/g	pH 5, 30°C, 240 min	95+	Very Low	Better for Cr(VI), optimal dose 0.1g,

							0.250mm size
Garlic Peel	Biosorbent	Methylene Blue	142.86 mg/g	pH 6-7, 50°C	**99**	Very Low	Highest capacity, natural antimicrobial compounds
Okra Waste (Food Canning)	Biosorbent	Pb(II)	High	pH 4-6, Room temp	**99**	Very Low	Ion exchange mechanism, hydroxyl complexes
HPP-DETA (Diethylenetriamine-Modified)	Synthetic	Methylene Blue	Slightly Superior	Optimized	High	Very High	Enhanced performance but prohibitive cost, limited commercial use
AQSOA-Z05 Zeolite Hydrogel Composite	Synthetic	Methylene Blue	Slightly Superior	Optimized	High	Very High	High performance but expensive, not commercially viable

Table 6: Adsorption capacities, operating conditions, and limitations of different vegetable-waste-based adsorbents

Adsorbent Source	**Target Pollutant**	**Adsorption Capacity (mg/g)**	**Operating pH**	**Temperature (°C)**	**Contact Time (min)**	**Key Advantages**	**Limitations/Challenges**
Potato Peel Waste	Pb(II)	125-148	4.5-5.5	25-45	30-120	Low cost, effective heavy metal removal,	Limited reusability, requires

						high surface area after activation	activation, variable composition
Coconut Husk	Cd(II), Cr(VI)	85-200	5-7	25-60	60-180	Abundant, high carbon content, effective for multiple pollutants, biodegradable	Slow kinetics, requires pretreatment, pH sensitive
Carrot Peel	Cu(II), Zn(II)	95-160	5-6	20-40	45-90	Cheap, readily available, effective heavy metal adsorption	Low mechanical strength, short saturation time, narrow pH range
Tomato Processing Waste	Dyes (Methylene Blue)	180-250	2-8	25-55	30-120	High dye removal capacity, wide pH range, abundant in food industry	Weak acid group interference, requires chemical modification for heavy metals
Banana Peel	Pb(II), Zn(II), Cd(II)	110-185	4-6.5	25-50	45-180	Eco-friendly, free or low cost, biocompatible, multiple adsorption sites	Low thermal stability, pH dependent, weak acid leaching
Onion Skin	Ni(II), Pb(II)	98-140	5-7	25-45	60-150	High cellulose content, abundant waste stream, effective metal removal	Lower capacity than synthetic adsorbents, requires drying
Rice Husk	As(V), Cr(VI), Pb(II)	42-156	3.5-7	25-60	30-120	Massively available in agriculture, contains silica, cost-effective	Lower capacity as-is, requires activation, ash management issues
Sugarcane Bagasse	Pb(II), Cu(II), Dyes	78-220	4-7	20-50	30-90	Massive waste volume, high cellulose, good	Variable properties, requires

						for dye removal, cost-effective	optimization, leaching of organic compounds
Peanut Shell	Cu(II), Pb(II), Ni(II)	85-175	5-7	25-45	60-120	Agricultural byproduct, high carbon, biodegradable, decent metal removal	Lower capacity than activated carbon, pH sensitive, fouling risk
Corn Cob/Stover	Cr(VI), Pb(II), Dyes	65-190	2-7	25-55	30-180	Highly abundant agricultural residue, versatile, low cost, effective activation	Variable sorption properties, silica content, ash handling required
Orange Peel	Pb(II), Cu(II), Cd(II)	75-135	4-6.5	25-45	45-120	Inexpensive, limonene provides functional groups, biodegradable	Lower capacity than coconut, moderate pH sensitivity, short contact time needed
Apple Pomace	Cu(II), Zn(II)	92-160	5-6.5	25-45	30-90	Food processing byproduct, good capacity, porous structure	Limited pH range, requires drying, variable composition between batches

Table 7: Other major waste water pollutants

Pollutant Category	**Examples**	**Sources**	**Health/Environmental Effects**
Nutrients	Nitrogen (N), Phosphorus (P)	Fertilizer runoff, human waste, detergents	Eutrophication, algal blooms, oxygen depletion in water bodies
Pathogens	Bacteria (*E. coli*, *Salmonella spp.*)	Human/animal feces, sewage	Gastrointestinal infections, disease outbreaks

	Viruses (Norovirus, Rotavirus)	Human/animal feces, sewage	Viral infections, diarrhea
	Protozoa (*Giardia spp.*, *Cryptosporidium spp.*)	Animal/human feces, sewage	Parasitic infections, severe diarrhea
	Helminths (Roundworms, Tapeworms)	Human/animal feces, sewage	Parasitic infections, malnutrition
Pharmaceuticals	Antibiotics	Hospital & household wastewater	Antibiotic resistance, bioaccumulation
	Hormones (Estrogen, Testosterone)	Contraceptives, HRT, animal feed	Endocrine disruption, reproductive issues in aquatic life
	Pain relievers (Ibuprofen, Acetaminophen)	Household medication disposal	Aquatic toxicity, bioaccumulation
	Antidepressants (SSRIs)	Household wastewater	Neurological effects in aquatic organisms
	Statins	Household wastewater	Potential ecological impacts

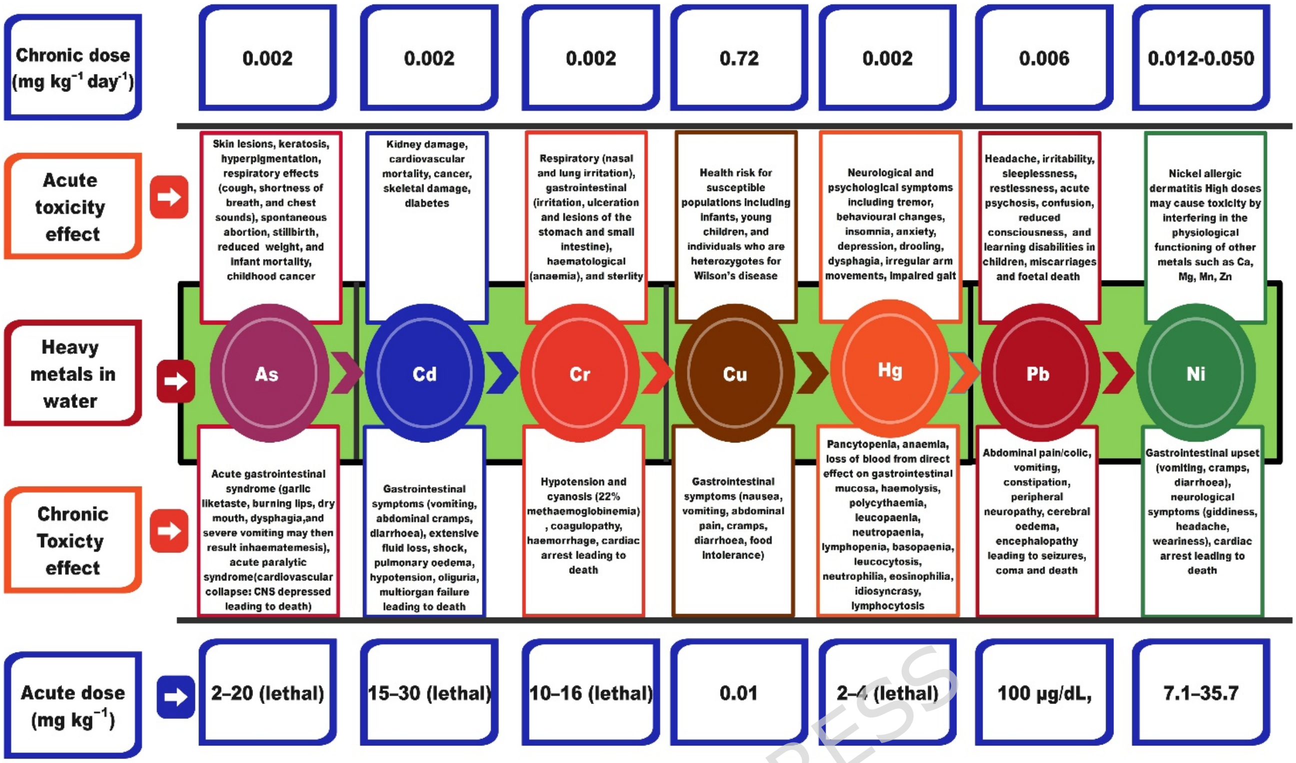

Fig. 1. Impact of heavy metal on human health

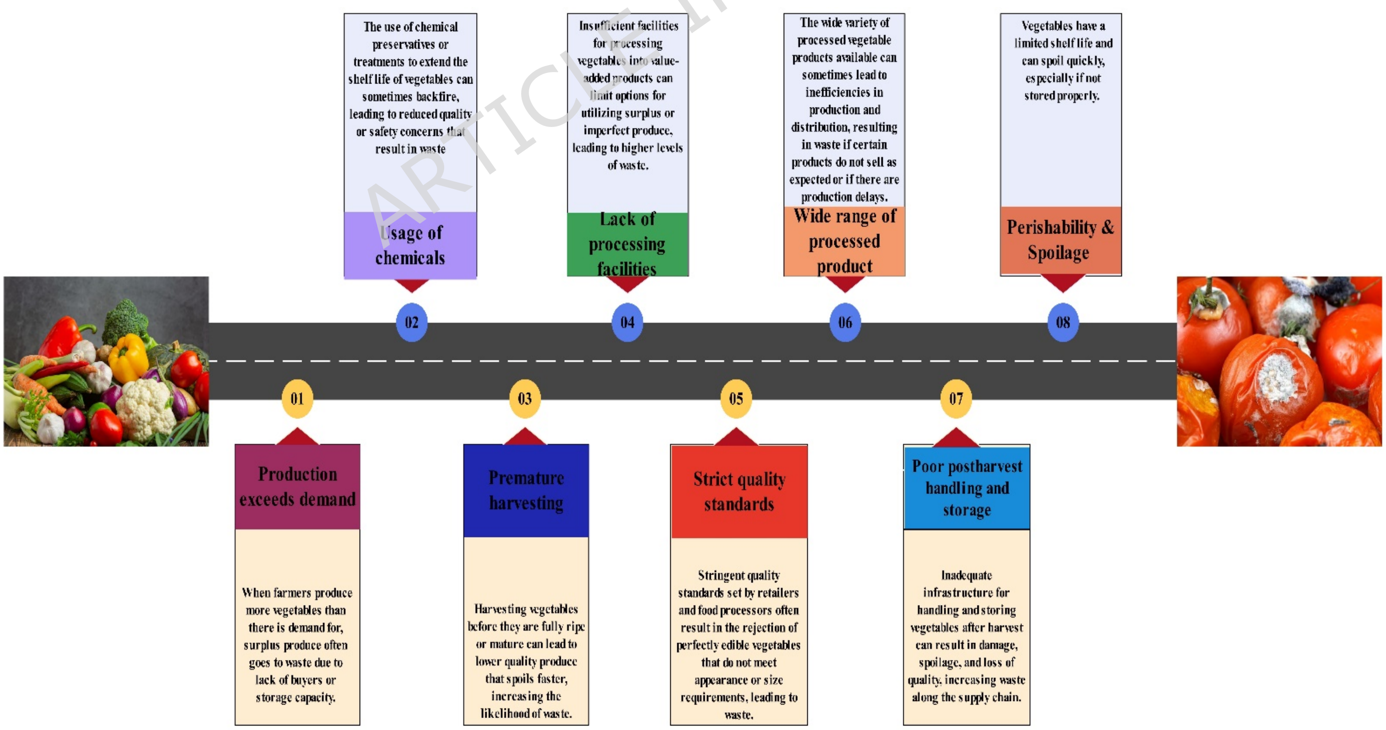

Fig. 2. Causes of vegetable waste residues

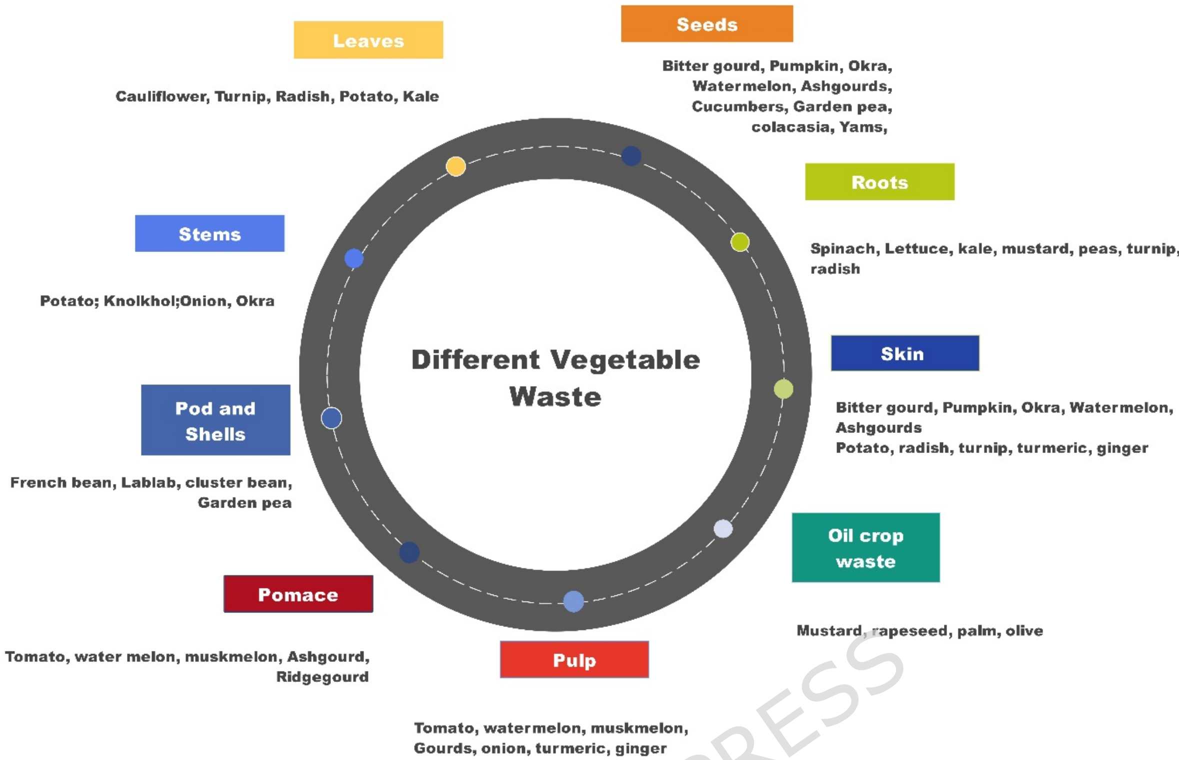

Fig. 3. Different types of vegetable biowaste

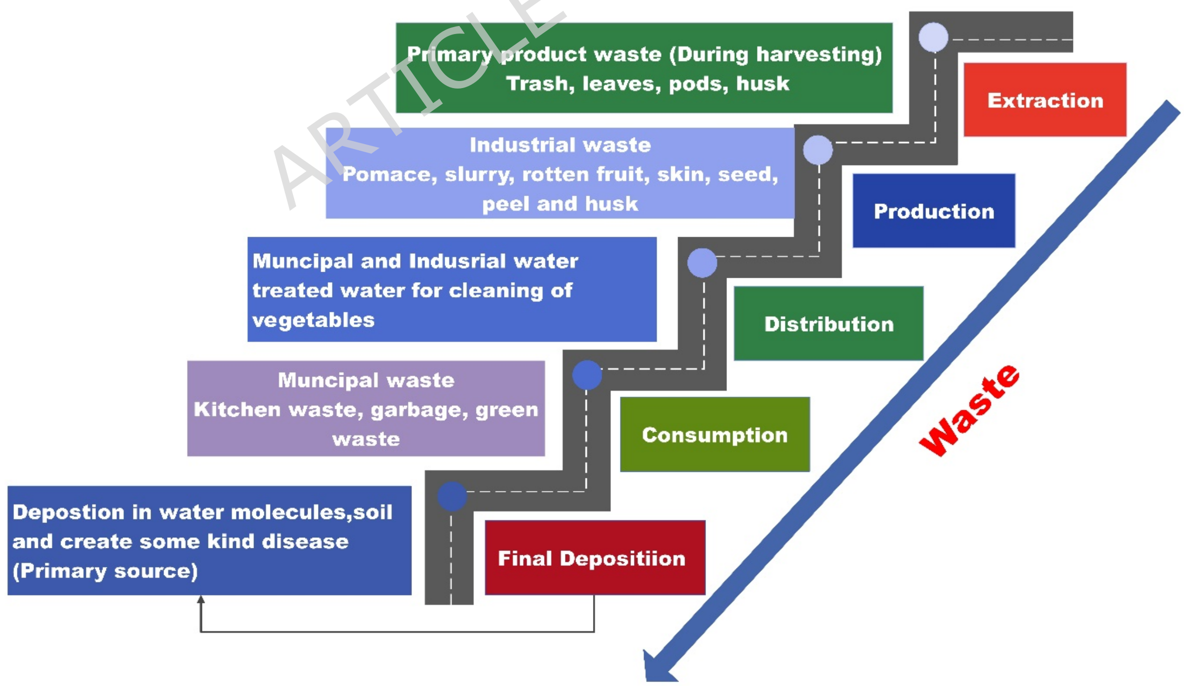

Fig. 4. Levels of vegetable waste in the environment

Water pollution	Solid or liquid waste pollutes	Aquatic life in rivers, lakes and sea
Soil pollution	Solid waste	Undesirable changes in soil composition
Air Pollution	Foul smell in air	Malodorous compound in air
Unhygienic conditions	Breeding of pathogenic microbes, flies, moquitoes and rodents	Unhealthy environment and spread of an epidemic
Aesthetics	Solid waste	Loss of aesthetic value of an area

Fig. 5. Impact of Vegetable Waste on different Components of the environment

Fig. 6. Linkage of vegetable Biowaste adsorbent with different SDGs