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Advances and future perspectives in biotechnological and bioconversional of dates byproducts

Khalid Hamid Musa [a,1], Ahmed A.M. Elnour [b,c,1,*]

[a] Department of Food Science and Human Nutrition, College of Agriculture and Food, Qassim University, Buraydah 51452, Saudi Arabia
[b] Centre of Excellence for Advanced Research in Fluid Flow (CARIFF), Universiti Malaysia Pahang Al-Sultan Abdullah (UMPSA), Malaysia
[c] Faculty of Chemical and Process Engineering Technology, Universiti Malaysia Pahang Al-Sultan Abdullah (UMPSA), Malaysia

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ABSTRACT

Background: Date production poses significant environmental and economic problems. Conventional waste management methods are insufficient to address these issues. However, microorganisms can convert date waste into valuable products, thus making bioconversion a sustainable solution.
Objective: This study investigated how bioconversion processes can manage date byproducts, focusing on producing beneficial compounds and nutrients in different industries. In addition, it emphasizes the importance of protecting the environment and managing waste responsibly in the data industry.
Methods: This study studies recent research on bioconversion processes using fungi and bacteria to convert date waste into bioactive compounds, enzymes, and polysaccharides. It determines whether these products can be used in different sectors, such as food, pharmaceuticals, and cosmetics. It examines methods for producing energy and recycling materials such as biogas, electricity, and biofuels.
Results: Bioconversion processes can transform date waste into valuable resources, thereby benefiting the economy and the environment. Research has demonstrated the successful production of antioxidants, enzymes, and polysaccharides from date waste, with applications in multiple industries.
Conclusion: Repurposing food waste as a useable resource reduces waste and opens up new economic opportunities. By leveraging the capabilities of microorganisms, waste can be converted into valuable products, thereby contributing to environmental preservation and economic advancement. Improving biotechnology to hone bioconversion processes and to make them cheaper is essential.
Recommendation: To maximize the potential for bioconversion, concerted research and development endeavors are essential. Priority should be given to refining bioconversion processes, innovating new products, and addressing the challenges associated with implementation and regulation, especially in developing nations. Researchers, industries, and policymakers must collaborate to manage date waste and promote sustainable development through bioconversion.

1. Introduction

Date production produces significant byproducts that present environmental and economic challenges [1]. Substantial byproducts intensify the industry's environmental impact, necessitating sustainable waste management solutions [2]. Sustainable waste management and environmental protection are crucial to address these industry challenges. Utilizing bioconversion processes to convert date byproducts into valuable energy sources can promote sustainable waste management practices and create economic opportunities in regions where the date is grown. Waste can be transformed into a sustainable feedstock for energy generation, producing recycled products, biogas, electricity, and biofuels [3]. Several challenges must be addressed to achieve efficient and sustainable waste management. Specific strategies are crucial for converting date byproducts into sustainable energy and boosting the economic growth in these regions.

The utilization of date byproducts to produce bioactive compounds has been demonstrated in various experiments [3], providing bioactive compounds and dietary fiber in date fruit byproducts., these studies demonstrate how agri-food waste can be used to produce value-added products for use in a variety of industries. Dhaouadi et al. described

* Corresponding author. Centre of Excellence for Advanced Research in Fluid Flow (CARIFF), Universiti Malaysia Pahang Al-Sultan Abdullah (UMPSA), Malaysia.
E-mail addresses: k.musa@qu.edu.sa (K.H. Musa), adamhassan@umpsa.edu.my (A.A.M. Elnour).
[1] Authors with the same contribution.

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Abbreviations

AA	Acetic acids
AI	Artificial intelligence
BC	Bacterial cellulose
CA	Citric acid
CE	Circular economy
GA	Glutamic acid
HFS	High-fructose syrup
LA	Lactic acid
LWEF	Land, Water, Energy and Food
ML	Machine learning
OA	Organic acid
RSM	Response Surface Methodology
SCO	Single-cell oil
SDG	Sustainable Development Goals
SHF	Separate Hydrolysis and Fermentation
SSF	Simultaneous saccharification and co-fermentation
UPLC	Ultra-performance liquid chromatography
USDA	United States Department of Agriculture
XG	Xanthan gum
XOS	Xylooligosaccharides

the biochemical composition and biological activity of date palm seeds and highlighted their potential use as bioactive compounds [4]. Date byproducts provide strong support for their use in a variety of industries to produce bioactive compounds. The advantages of bioconversion processes, particularly regarding the bioconversion of biomass, have been extensively documented in scientific literature. There is still a need for further research and attention in the areas of optimizing bioconversion processes to enhance their efficiency and cost-effectiveness as well as to develop new products.

The purpose of exploring the current state and prospects of bioconversion techniques for date byproducts is to contribute to sustainable waste management and stimulate economic growth (SDG8). This is supported by a growing body of evidence on global food waste, which has negative consequences for sustainability [5]. This study aims to establish long-term strategic waste management plans and assess the implementation and achievement of waste management practices in the short term [6]. Another goal of this study was to develop sustainable and efficient waste management systems to reduce the harmful effects of waste [7]. This study emphasizes the role of bioconversion in achieving sustainability and economic growth through strategic waste management.

Transforming agricultural byproducts, such as date palms, into high-value items via bioconversion processes, such as saccharification and fermentation, is essential for reducing the environmental pollution caused by these byproducts [8]. Despite numerous advancements, there is still a need to enhance the efficiency and cost-effectiveness of bioconversion-processing pathways. Most comparisons between these pathways are based on empirical data [9]. Recent scientific trends are shifting toward an integrated overall bioconversion process aimed at maximizing output, expanding the range of fermentation products, and broadening applications [10]. The efficient and diverse bioconversion of agricultural byproducts is crucial for both environmental and economic benefits.

The central aim of this study was to conduct an extensive examination of bioconversion processes for date byproducts, while simultaneously identifying potential areas for further investigation and enhancement. It is also possible to recycle food waste in urban areas by converting waste food and sludge into lactic acid (LA). Additionally, the conversion of organic waste and agri-food transformation byproducts into sustainable and nutritionally beneficial proteins and lipids using *Hermetia illucens* larvae is a promising approach [11]. These studies provide evidence to support the current state of bioconversion processes for date byproducts and highlight the potential for future research and development in this field.

Improving bioconversion methods for date byproducts could potentially lead to a surge in the production of bioactive compounds and the creation of novel products, thereby fostering sustainable waste management and stimulating economic growth [12]. Numerous studies have highlighted the positive impact of human capital, which encompasses aspects such as education and health (SDG 3 and 4) and economic growth (SDG8), thereby emphasizing the significance of these factors in driving economic development [13]. Furthermore, research has revealed that agricultural growth is correlated with an improvement in total factor productivity, which ultimately contributes to overall economic growth [14]. These findings support the hypothesis that optimizing bioconversion processes can drive economic growth through the development of new products and sustainable waste management practices.

2. Dates waste management and united nations sustainable development goals

Waste management for dates involves organized collection, transportation, processing, and disposal of waste materials generated by the industry [15]. Minimize environmental impacts and ensure sustainability through collection, segregation, composting, and disposal [16]. The United Nations introduced 17 SDGs in 2015, aiming to ensure prosperity, safeguard the environment, and eliminate poverty for all individuals [17]. SDG 12 targets sustainable consumption and production, emphasizing responsible resource use and waste reduction to minimize environmental impacts. Achieving this goal complements the SDGs and promotes a sustainable future by implementing efficient waste management practices [18]. Reducing food waste and promoting sustainable practices in the food industry are crucial for achieving the UN SDGs by 2030 and building a sustainable bioeconomy [19]. Efficient valorization of food waste requires essential resources such as energy and water [20]. Agro-waste management, which is crucial for development, minimizes environmental impact, conserves resources, and reduces waste.

Using circular and sustainable processes to create products and materials is crucial for achieving the SDGs by utilizing food waste [21]. Considering the entire life cycle of a product, from raw material sourcing to eventual disposal or reuse, it is possible to minimize waste and maximize resource efficiency [22]. Maximizing food waste utilization via biorefineries and circular processes can help achieve the UN SDGs by reducing greenhouse gas emissions, conserving resources, and supporting local economies. Successful implementation requires government intervention through policies and legislation [23]. Managing energy and water in a circular economy (CE) is crucial for achieving the UN SDGs.

Reduce food waste by considering all stages from production to processing and distribution [24]. Sustainable circular processes reduce waste, improve resource efficiency, and create new products and revenue from food waste [25]. Such policies could valorize waste to mitigate environmental damage. These policies motivate waste resource use, stimulate innovation in waste processing, and promote circular practices in the food industry [26]. Government policies and innovations are required for sustainable food industry practices. Developed countries primarily attribute food waste to consumer behavior, whereas developing nations attribute it to a lack of technological capability [27]. Biorefineries can provide energy and sustainable waste management using a closed-loop process to convert waste energy into valuable products [19]. Thus, innovative policies and technologies are key to reducing food waste and enhancing sustainability.

Date pits represent approximately 10 % of the total weight of date fruit [22]. Date fruit production generates substantial waste, causing environmental issues in the date processing industries [28]. Further research is necessary to explore the potential benefits of pit waste and its impact on the environment and human health [23]. Reducing date fruit waste is critical for sustainable development and achievement of SDGs. This shift aims to improve sustainable development and production objectives, while reducing material and chemical expenses. Date fruit, commonly marketed as a premium confectionery, remains an important subsistence crop [29]. Eco-friendly material production is vital for bioeconomy and sustainable SDGs [30]. Thus, sustainably utilizing date pits and agricultural waste supports CE and promotes sustainable development. The UN Sustainable Development Goals (SDGs) and waste management systems are shown in Fig. 1.

3. Nutritional facts and biochemical markers of date waste

Essential nutrients such as carbohydrates, proteins, fats, vitamins, and minerals are vital. Biochemical markers in food, which indicate nutritional value and health benefits, are crucial [25]. The nutritional content of date waste varies based on factors such as date variety, processing techniques, and storage conditions [31]. Dates are nutrient-rich despite their sugar content; they offer fiber, carbohydrates, vitamins, minerals, and antioxidants [32]. The nutritional and biochemical composition of date waste can be affected by processing, storage, and contaminants [33]. Date fruits offer essential nutrients, including carbohydrates, minerals, fiber, vitamins, and beneficial compounds, such as amino and fatty acids, phenols, flavonoids, anthocyanins, and tannins [34]. These components offer advantages such as improved digestion, antioxidant support, and anti-inflammatory properties [35]. Research should focus on using date waste byproducts via bio-processing technologies such as fermentation or enzyme processing to create value-added items. Assessing the biochemical makeup of substrates is crucial for optimal outcomes [36]. Therefor, bio-processing date waste can yield valuable health products.

Vermicompost enhances date palm fruit quality in Saudi Arabia[37]. A 58 biodegradable starchy date waste can create vermicompost as a carbon source[38]. Lignocellulosic biomass is utilized in biofuels and biochemicals to manage waste and utilize resources[5]. Karki et al. examined the biochemical parameters and synergistic outcomes of anaerobic co-digestion involving commercial food waste and dairy manure[39]. In one study, five ratios of agro-waste and date palm leaves were used to examine their impact on the resulting product, with ratios of 0:100 %, 25 %:75 %, 50 %:50 %, 75 %:25 %, and 100 %:0 %[40]. Daily, the date industry discards large quantities of date waste, including 10 % pits, causing environmental issues[41]. Composting date palm waste, pits, and crustacean shells in containers reduces date fruit waste by 10 %[42]. Researchers have explored blending agricultural waste with date palms and have assessed their potential as DNA markers for identifying Basidiomycota[16]. Thus, investigating the advantages of composting date pits is a promising approach.

4. Date waste pharmaceutical activity and its biological applications

Date waste contains active ingredients such as production, packaging, and consumption [43]. Application programming interfaces (APIs) may have biological effects on the environment, which can affect the health of living organisms. Ecotoxicology explores API's effects of APIs on ecosystems, and date waste-derived APIs foster environmentally friendly plant growth. Phenolic compounds are used in medicine and food because of their antiviral, antibacterial, antioxidant, anticarcinogenic, and anti-inflammatory properties [44]. Food waste can be processed by various methods. Paper mill sludge-derived granular activated carbon effectively removes pharmaceuticals from wastewater [45]. Hemicelluloses improve biomedical applications owing to their specific biological functions, such as antioxidant, antitumor, and immunomodulatory effects [46]. Celluloses, hemicelluloses, lignins, and volatiles in plant waste can also play a role in these applications [47].

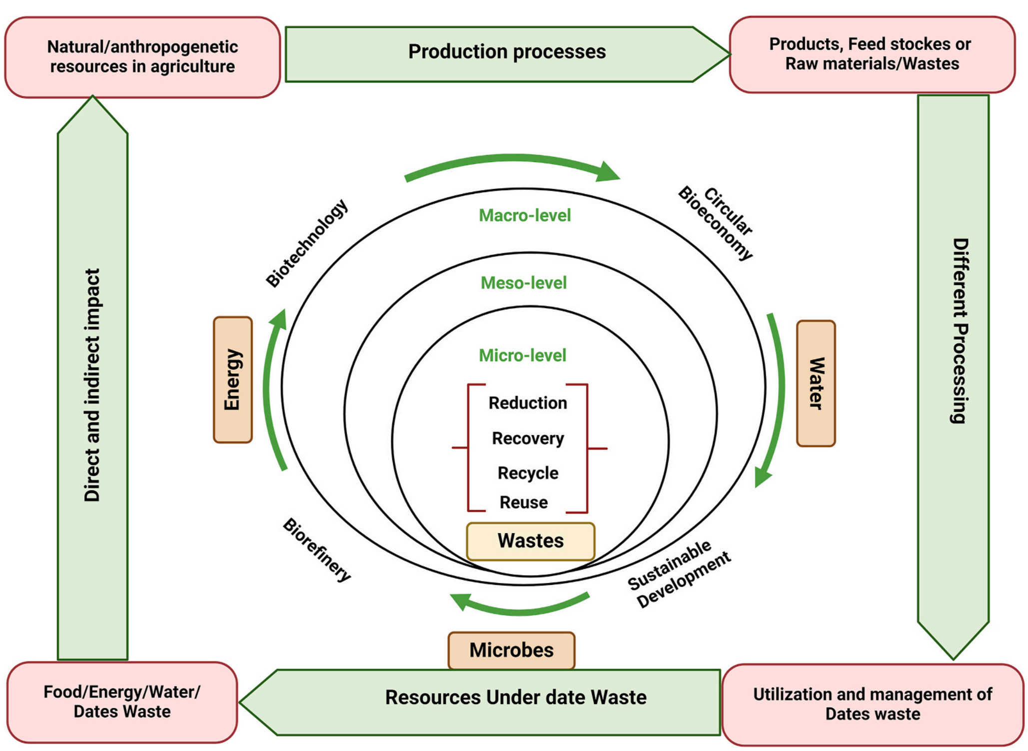

Fig. 1. The agro-waste cycle starts with formation after human activity at the micro- (farm), meso-(company/industrial), or macro- (city-to-country) levels with different pathways under the 4Rs (reduce, recovery, reuse, and recycle) rules, with different possible applications and suggested management under different nexuses. The main factors that control the processing, transformation, conversion, and production of byproducts or new products from agro-waste include water, energy, and microbes.

Polysaccharide hydrocolloids, such as xanthan gum, are commonly used in pharmaceuticals and wastewater treatment and can enhance antibacterial activity [37]. Therefore, waste-derived compounds are versatile in terms of both industry and health.

Date palm fruit waste may produce pharmaceutical compounds, and the 25:75 ratio of date palm to agro-waste produced the highest yield, number of fruiting bodies, and biological efficiency compared to other ratios [40]. Activated carbon from black wattle bark waste effectively absorbed phenol. A 25:75 ratio of wheat straw to date palm optimizes most parameters [37]. Date press cake-derived activated carbon was used to evaluate Cr (VI) adsorption [48]. Thus, date palm byproducts offer the potential for drug development and eco-friendly applications.

Exopolysaccharides(EPS) is used in various sectors such as detergents, food, paper, textiles, leather, biofuels, petroleum, pharmaceuticals, cosmetics, and wastewater treatment [49]. The unique features of bacterial EPSs, such as their ability to create matrices and inherent biological activity, can affect the development of novel drugs [50]. Identifying suitable applications for date palm fruit waste is crucial for mitigating its environmental impacts [51]. Few studies on date fruit use exist, mainly focusing on its chemistry, pharmacology, phytochemical industries, nutritional value, and health advantages [52]. Hence, date palms play crucial environmental and industrial roles.

5. Products and byproducts during the processing of date palm fruits

Various date palm fruit products, including date syrup, paste, and dried dates, are obtained from fruit processing [31]. Industrial processes can use byproducts, such as leaves, stems, and fruit fibers for biofuel and activated carbon production [21]. However, date palm fruit processing can result in significant losses owing to picking, storage, and conditioning practices [53]. Utilizing bio-processing technology, date palm fruit byproducts, such as seeds, fibers, skin, and leaves, can minimize waste [54]. These byproducts have diverse applications including animal feed, fuel, composting, and activated carbon production.

Limited research has been conducted on the use of fruit waste as a substrate for fermentation to produce carotenoids [55]. Researchers are exploring ways to use discarded parts for microbial fermentation to produce carotenoids [38]. Date byproducts are completely valorized to produce hydrogen, methane, and date syrup (35.5% sucrose, 11.8 % glucose, and 13.17% fructose) through hot water extraction, generating 292 mL H_2/g VS [56]. Generating biofuels by promoting lipid accumulation in the oleaginous yeast *Rhodotorula glutinis PTCC5256* cultivated on date syrup derived from low-grade date palm fruits [57]. Date palm fruit waste can replace glucose for *Lactobacillus* growth and biomass production, offering efficient waste management solutions for the date and date processing industries [20]. Therefore, the production of biofuels from yeast and date syrup is urgently needed to manage date palm waste.

Vieira et al. evaluated the impact of sterilization techniques and supplementation on oyster mushroom cultivation and storage using date palm waste as the substrate [58]. Low-quality date fruits produce biomaterials through the fermentation of date palm fruits with no stones, immersed in warm distilled water at 50 °C for 30 min [31]. Given its abundance in the date processing industry and the resulting environmental concerns, date palm fruits may serve as a future food source. Its nutrient content and significance in human nutrition make it an increasingly important global crop, as demonstrated in Fig. 2.

6. Current situation and challenges of date waste management

As global waste production continues to increase, waste management is facing a growing challenges [59]. Efficient methods are crucial for limiting waste, decreasing environmental effects, and supporting eco-friendly waste disposal [15]. Numerous approaches can be employed to enhance the sustainable management of date palm waste,

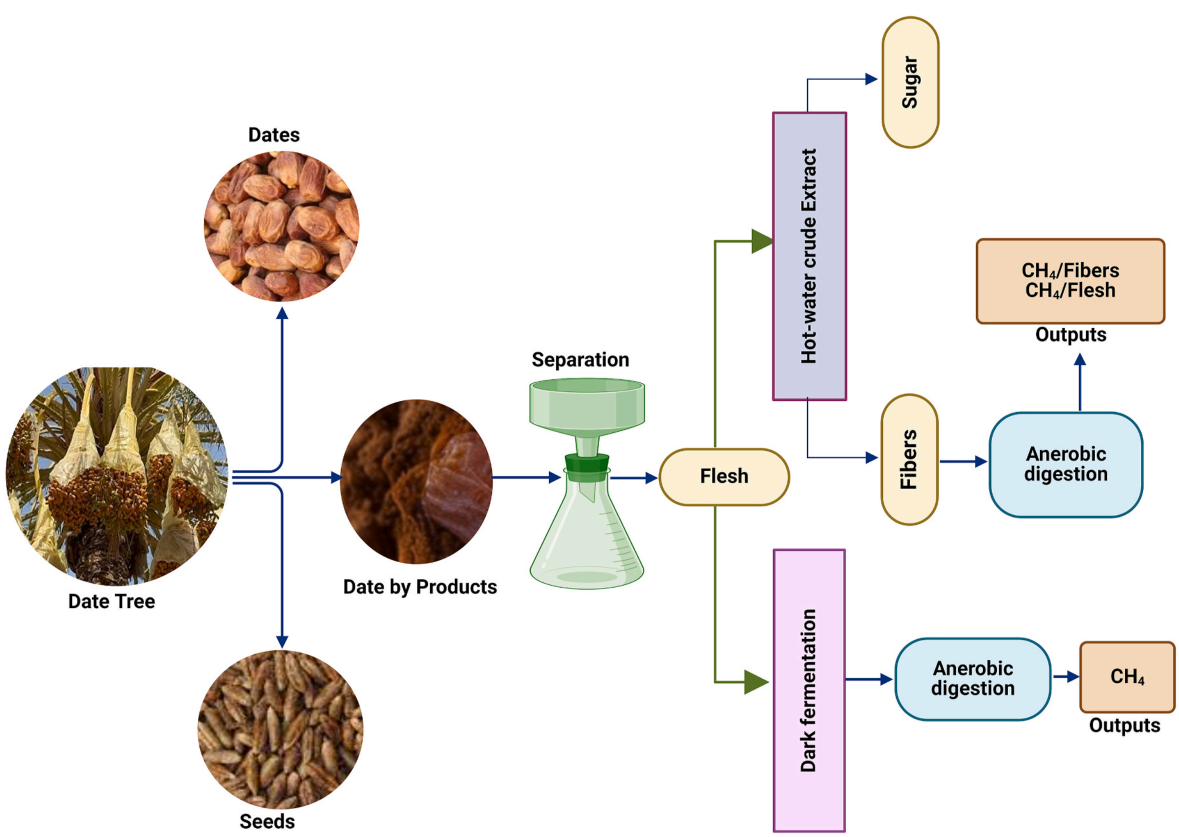

Fig. 2. demonstrates the steps of the sustainable bioconversion of date byproducts into biohydrogen, biogas, and date syrup.

for both economic viability and environmental sustainability. Such strategies include co-composting with urban and agri-food sludge [60], producing biochar for metal extraction [61], and creating bioethanol using *Saccharomyces cerevisiae* [62] and *Pichia kudriavzevii* strains [51]. Furthermore, date palm waste can be repurposed for graphene quantum dots [63], as a plant growth substrate [64], as compost for forage growth [65], and in engineering applications [66] to promote sustainability. However, challenges in date palm waste management exist, such as inadequate utilization leading to waste accumulation [67], disposal problems causing pollution [68], and limited incorporation into construction materials [69]. Therefore, waste management techniques including microbial electrolysis cells for refining waste and creating clean electrofuels are highly recommended.

Dhanya et al. studied microbial electrolysis cells for waste refinement and clean electrofuel generation for waste management [70]. Research conducted in Chinese provinces has mainly focused on environmental effects, food waste management, and life cycle assessments of waste disposal systems [71]. Livestock waste poses environmental risks owing to harmful pathogens and antibiotic residues, and effective management is necessary [72]. The utilization of agricultural and livestock waste, particularly through anaerobic digestion, for biogas production has recently gained significant interest and attention [73]. Efficient management of livestock waste is critical for mitigating pollution risks and promoting sustainable practices [74]. Thus, research is exploring new methods of efficient waste management.

The date palm and processing industries produce waste in the form of fallen fruits, seeds, and press cake [55]. To address this issue, researchers are exploring biowaste for bioenergy. Chen et al. conducted extensive research on converting waste into fungal endophytes in Orchidaceae plants [75]. The food-energy-water nexus is vital for managing food waste, and sustainable waste-to-energy and nutrient recycling methods have been suggested [76]. Logistics, infrastructure, and bioresource management can address waste's challenges year-round [26]. Recently, Jamil et al. explored the current state, challenges, and future possibilities of biofuels and biochemicals [77]. However, the commercial production of second-generation biofuels still faces significant challenges [78]. addressing the challenges of transitioning to a bioeconomy and adopting alternative biofuels is a significant obstacle for both the scientific and industrial sectors, despite the advancements in technology that promote a circular bioeconomy for sustainable growth, as depicted in Fig. 3.

7. Bioprocess of date waste and its value-addition

Fermentation, composting, and anaerobic digestion convert date waste into valuable items such as biofuels, biochemicals, and organic fertilizers [55]. Value-added food and nutraceutical industries use the bio-processing of date fruit waste and byproducts. Guajardo et al. investigated the potential biocatalysts extracted from date fruit [79]. Kouhsar et al. recognized potential business opportunities in countries with large-scale date palm cultivation, concentrating on waste management and resource optimization [47]. Converting date fruit waste into valuable products via bio-processing is crucial.

Implement segregation strategies for enhanced date waste management and value-added potential. Two alternatives for bioethanol and butanol production are consolidated bio-processing: simultaneous saccharification and co-fermentation (SSF) and SHF [80]. Hence, *Clostridium strains* may increase isopropanol-butanol production from glucose and hemicellulose through CBP.

Date fruits, often viewed as luxury sweets, also serve as subsistence crops in arid regions. Recently, date palm leaf waste and other agricultural wastes from Saudi Arabia to create a high-protein value-added product using *P. ostreatus mushrooms* [81]. They valorized resources via integrated bioprocesses with food and vegetable waste co-digestion. In this study, we assessed the feasibility of enhancing the value of hard dates by exploring their compositional, functional, and sensory traits in

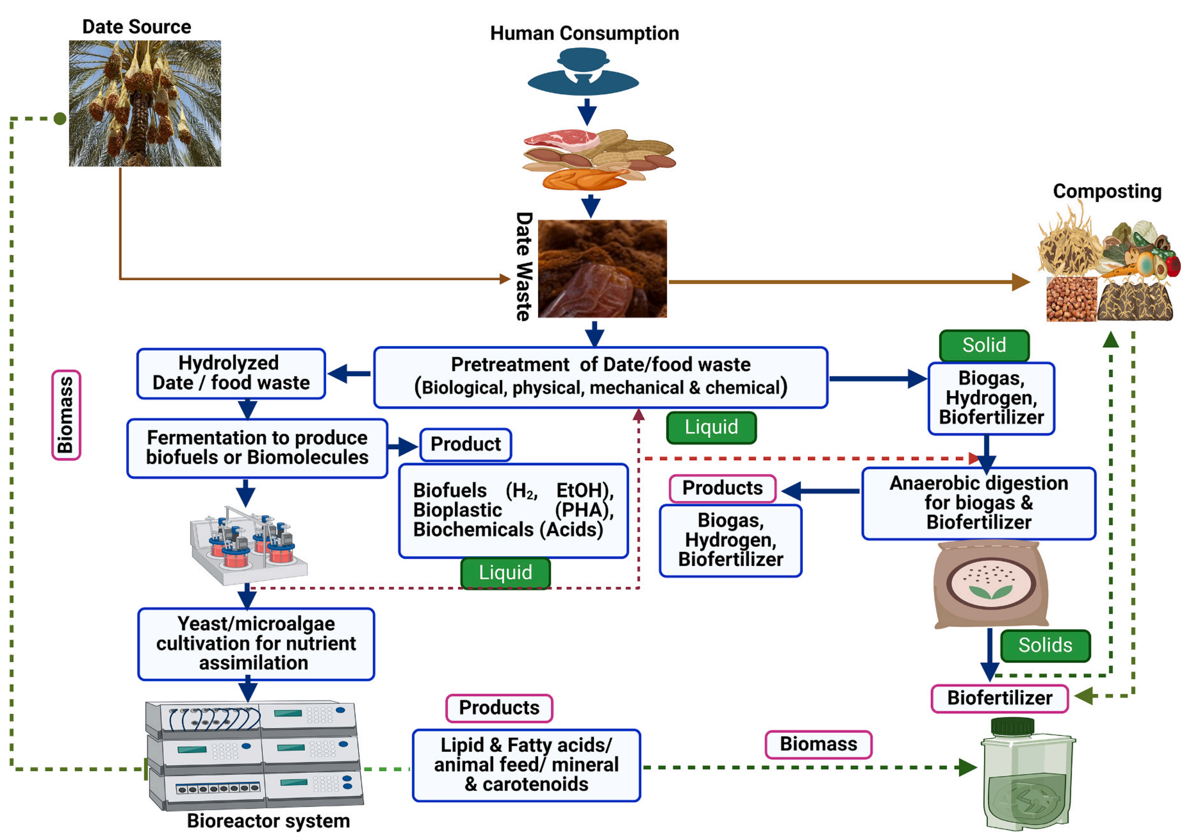

Fig. 3. General natural product waste valorization for biogas-based bioenergy production in circular bioeconomy opportunities, challenges, and future development.

date jams [82]. Focusing on date pits, a by-product often seen as useless, comprising 10 % of the entire date fruit. Date palm fruit harvesting results in significant waste, raising environmental concerns. This waste, comprising 50–70 % of the raw material weight, contains valuable biomolecules such as carotenoids and nutrients. Karimi et al. investigated the use of waste biomass as a cost-effective source of high-end bio-based products [83]. Despite research on date palm cultivation and utilization, only a few studies have examined date chemistry, pharmacology, and its health benefits. Consolidated bio-processing can convert waste into bioethanol and butanol, offering alternatives to Simultaneous Saccharification (SSF) and Separate Hydrolysis and Fermentation (SHF), such as merged bio-processing and co-fermentation.

8. Date palm fruits and fermented products

Fermentation converts fruit sugars into alcohols and organic compounds using yeast or bacteria [84]. Traditionally, fermentation technology has been employed to preserve food and create value-added products. By utilizing date palm fruits, this method can yield a range of products, such as wine, vinegar, alcohol, and organic acids(OA) [85]. Date processing can create value by using bio-processing technology to convert byproducts and waste. A previous study demonstrated carotenoid production from date byproducts through microbial fermentation optimization [21]. Date palm juice fermentation with *Rhizobium radiobacter* ATCC 6466 yields Curdlan gum [86]. Fermentation efficiently converts date palm byproducts into valuable substances.

Date fruits can create functional biomaterials via fermentation with date syrup as the substrate[50]. Reduces waste by creating valuable resources from date palm fruit harvesting. Steep stone-free fruits in warm water at 50 °C for 120 min to produce 10 L of date syrup per kg of initial low-quality fruits[31]. Dates are widely cultivated and consumed owing to their high nutritional content. In Oman, Al-Yahyai et al. accounted for 82 % of the country's fruit crop production, whereas date pits, a by-product, comprise an average of 10 % of the total date output [87]. Thus, data-rich regions sustainably and waste-reducing use low-quality biomaterial.

8.1. Date waste and its associated microbes

Date waste can have significant consequences on associated microbes. Research has demonstrated that the utilization of date fruit waste by microbial species results in the production of value-added products [88]. Nevertheless, these wastes have been linked to negative effects on soil microbial populations, aquatic ecosystems, and air quality [89]. The microbiota in the environment, such as food waste, can affect the performance of larvae, with changes in the microbiota influencing larval biomass [90]. Overall, interactions between date waste and its associated microbes can have substantial effects on ecosystems and microbial communities.

8.2. Dates waste biofuel opportunity production

Biofuel production from waste materials, including organic waste, offers a sustainable solution for increasing energy production while reducing emissions [91]. Tree waste (20 kg per tree), rich in fructose, is a valuable feedstock for biofuel production. It also enables biorefining for biopolymers and other products [55]. Converting food waste into valuable products via immobilized enzymes fosters environmental sustainability while promoting a CE [21]. This study investigated the use of fermentation and enzyme processing technologies to convert date fruit waste into useful products, including biofuels, biopolymers, and industrial enzymes. The study also examines the advantages and challenges of these processes to determine if they are economically viable [92], and whether the potential of date waste is still not fully exploited [93]. Fast pyrolysis is a promising method for efficiently converting date palm waste into biofuels efficiently [67]. However, challenges, such as competition for use and the need for more research, hinder full utilization [94]. The lack of opportunities for sustainable energy and waste management by not fully utilizing date waste for biofuel production is inconvenient.

8.2.1. Date waste and bioethanol production

Bioethanol production from date waste aims to enhance delignification and enzymatic glucose conversion rates by fermenting crops, including corn and sugarcane. Organosolv pretreatment is a sustainable method for generating bioethanol through the delignification and saccharification of non-edible biomass [95]. Optimized organosolv fractionation maximized the conversion of hybrid poplar to ethanol and other products.

The fermentation potential of yeast strains for lignocellulosic biomass ethanol production was evaluated using response surface analysis, examining ethanol concentration and yield at 50 %, 65 %, and 80 % ethanol-water concentrations [95]. Bioethanol production depends on the high cellulose content in the biomass, which leads to greater bioethanol and lignin yields [19]. Bioethanol presents both ecological and financial advantages, rivaling the fuel market worldwide [96]. Several approaches, including wet oxidation and steam explosion, have been evaluated for bioethanol production from sugarcane bagasse [97]. Beta-glucosidases aid bioethanol production by degrading cellulose. El-Ramady et al. investigated eco-friendly electrochemical techniques for wheat straw delignification and assessed agro-waste's potential in bioenergy generation [15]. Santiago et al. studied orange peel waste utilization and improved silage for LA and bioethanol production [19]. The efficiency of cellulose saccharification and optimization of hydrothermal pretreatment affect bioethanol yields from lignocellulosic biomass [98]. Thus, bioethanol production via cellulose and pretreatment methods are necessary. Algal biomass sustainably powers biorefineries for renewable sugar production [26]. Romaní et al. investigated the potential of Paecilomyces for bioethanol production from lignocellulose through combined bio-processing, and utilized Ureibacillus thermophilus to purify waste house wood hydrolysate for bioethanol production [95]. Fig. 4 illustrates the production of bioethanol from waste.

8.2.2. Date waste and butanol production

Butanol, a type of alcohol with fuel and solvent applications, exists in various forms, such as normal, secondary, isobutanol, and tert-butanol. *Clostridium acetobutylicum* employs different production methods for butanol production from date waste, including continuous fermentation, feed starch retrogradation, and the direct butanol-forming route [99]. Distillation, microwaves, and other techniques remove acetone and ethanol and purify butanol from water [100]. The impact of residence time on total butanol production costs was minimal, whereas the butanol titer was key in determining these costs [101]. *Ralstonia eutropha* H16 has been shown to increase the production of higher alcohols, including isobutanol and 3-methyl-1-butanol [19]. Studies have employed empirical models to generate butanol through acetone-butanol-ethanol fermentation using *Clostridium saccharoperbutyl acetonicum* N1-4 and palm kernel cake as substrates, as shown in Fig. 5..

8.2.3. Date waste and hydrogen production

Hydrogen production includes biohydrogen from cellulose, co-cultures of hydrogen bacteria, genetically engineered bacteria, and distillery wastewater [102]. The environmental and economic aspects of hydrogen production were compared, focusing on alkaline water electrolysis and catalytic gasification of wheat straw [103]. Thus, affordable hydrogen production techniques can be simplified. Other studies have focused on optimizing hydrogen and lipid production from organic waste using thermal pretreatment, substrate loading, and immobilized microorganisms [104]. Three *thermosaccharolyticum* strains were

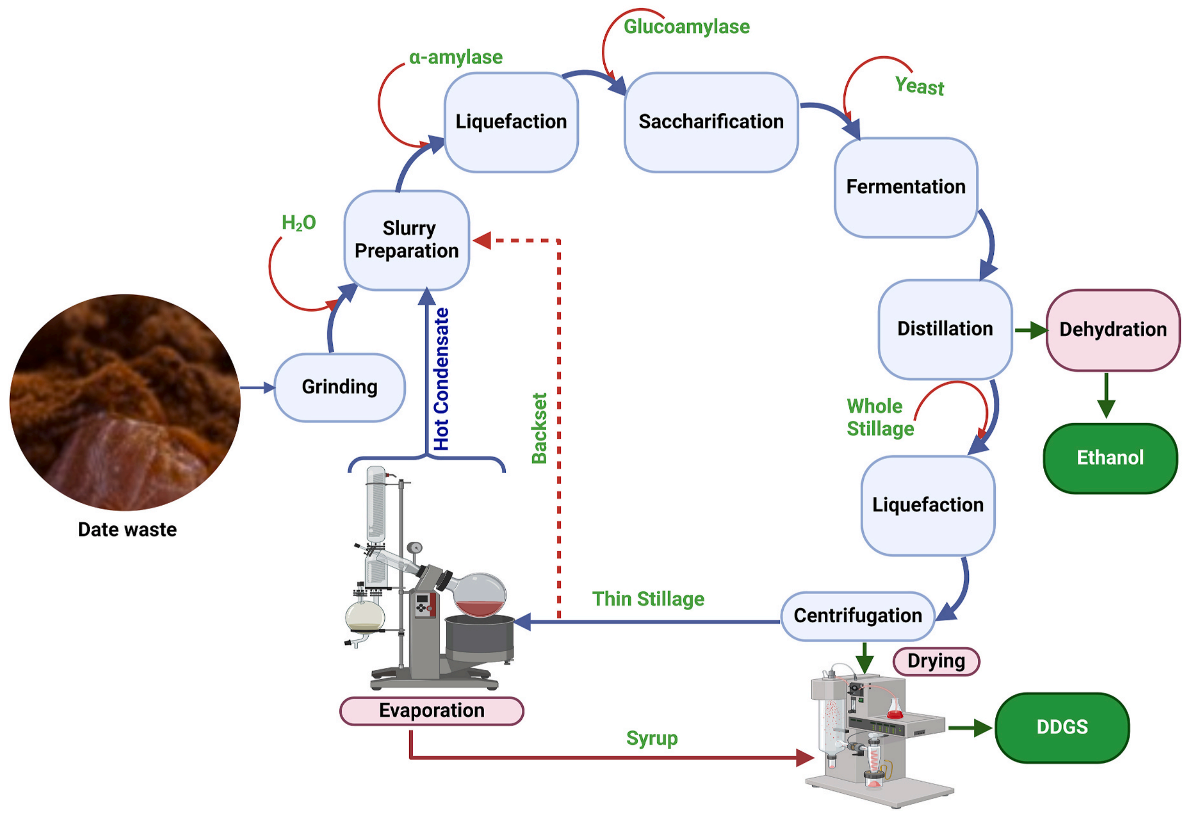

Fig. 4. Schematic of dry-ground ethanol production from waste.

isolated for sustainable hydrogen production from lignocellulose using organic materials, such as sugarcane bagasse, dates, organic waste, and rice husk [105]. Hydrogen production methods include ethanol steam reforming, catalytic valorization of lignin, and fermentation [96]. Cultural and environmental factors affect hydrogen production, and the environmental effects of various methods have been assessed [19]. Thus, research on hydrogen production from organic waste such as date highlights innovation and an environmental focus.

8.3. *Carotenoid extraction*

Carotenoids, natural plant pigments, are crucial for photosynthesis and coloring fruits and vegetables like reds, yellows, and oranges [21]. The optimal conditions for carotenoid production were pH 6.7 and salinity 3.5%, yielding 25.14 mg/L. The lowest production was 1.7 mg/L and 0.095 mg/L, respectively [21]. Romaní *et al.* studied agro-industrial waste as an eco-friendly growth medium using RSM to optimize *Rhodotorula* ATL72 growth, and examined the effects of pH, salinity, and temperature on carotenoid production [95]. The results showed that the ideal conditions for maximum carotenoid concentration (25.14 mg/L) were a pH of 6.7 and salinity of 3.5% [114]. The least effective conditions were observed in run 7, resulting in a minimum carotenoid concentration of 1.7 mg/L. To enhance carotenoid production, the Plackett–Burman design was employed to analyze yeast growth, focusing on *Rhodotorula* ATL72, a yeast that naturally generates numerous carotenoids but is not sufficient for commercial purposes [115]. These methods, including waste utilization, in vitro digestion, and microencapsulation, have been used to enhance carotenoid production [46]. Thus, advanced methods have boosted *Rhodotorula* ATL72's carotenoid production for commercial use.

8.4. *Date waste and biopolymers production*

The production of biopolymers from date waste transforms the waste generated during date fruit processing into valuable resources such as biodegradable polymers [106] Fermentation, enzymatic hydrolysis, and chemical modification can convert date waste into biopolymers such as polysaccharides, proteins, and biodegradable plastics [107]. Various methods can be employed to convert FW into biopolymers. These methods include extraction or fermentation, with or without pretreatment, to obtain fermentable sugars using solid-state fermentation [108]. Additionally, waste materials can be converted into polyhydroxyalkanoates (PHAs) as a feasible solution for biopolymer production [109]. Utilizing biowaste as a raw material can lead to the development of biorefineries, a key technology in the 21st century that reduces waste and diversifies food packaging materials [110]. By blending biopolymers extracted from fruit and vegetable wastes with other polymers, composite materials such as biocomposites can be created [111]. Furthermore, waste vegetable oils and fish skin can serve as alternative sources for biopolymer production [112]. The resulting biopolymers can be used in various industries such as agriculture, biomedicine, and food packaging [113]. Promoting sustainable development by reducing waste and creating income opportunities for rural communities.

8.4.1. *Curdlan*

Curdlan is a water-soluble polysaccharide obtained from *Agrobacterium* sp. It serves as a thickener and gelling agent in food, pharmaceuticals, and cosmetics [116]. Curdlan is a water-soluble polysaccharide from *Agrobacterium* sp. It functions as a thickener and gelling agent in food, pharmaceuticals, and cosmetics [117]. Curdlan and its derivatives have several applications. Curdlan gum is produced by fermenting date palm juice byproducts with Rhizobium radiobacter ATCC 6466 under optimal conditions, including pH 7, 2 g/L ammonium sulfate, 120 g/L date glucose juice concentration, 30 °C, 5 ml/100 ml inoculum ratio, 180 rpm agitation, and 51 h fermentation period, resulting in a yield of 22.83 g/L [103]. Hence, Curdlan's effective production and diverse uses underline its key industrial role.

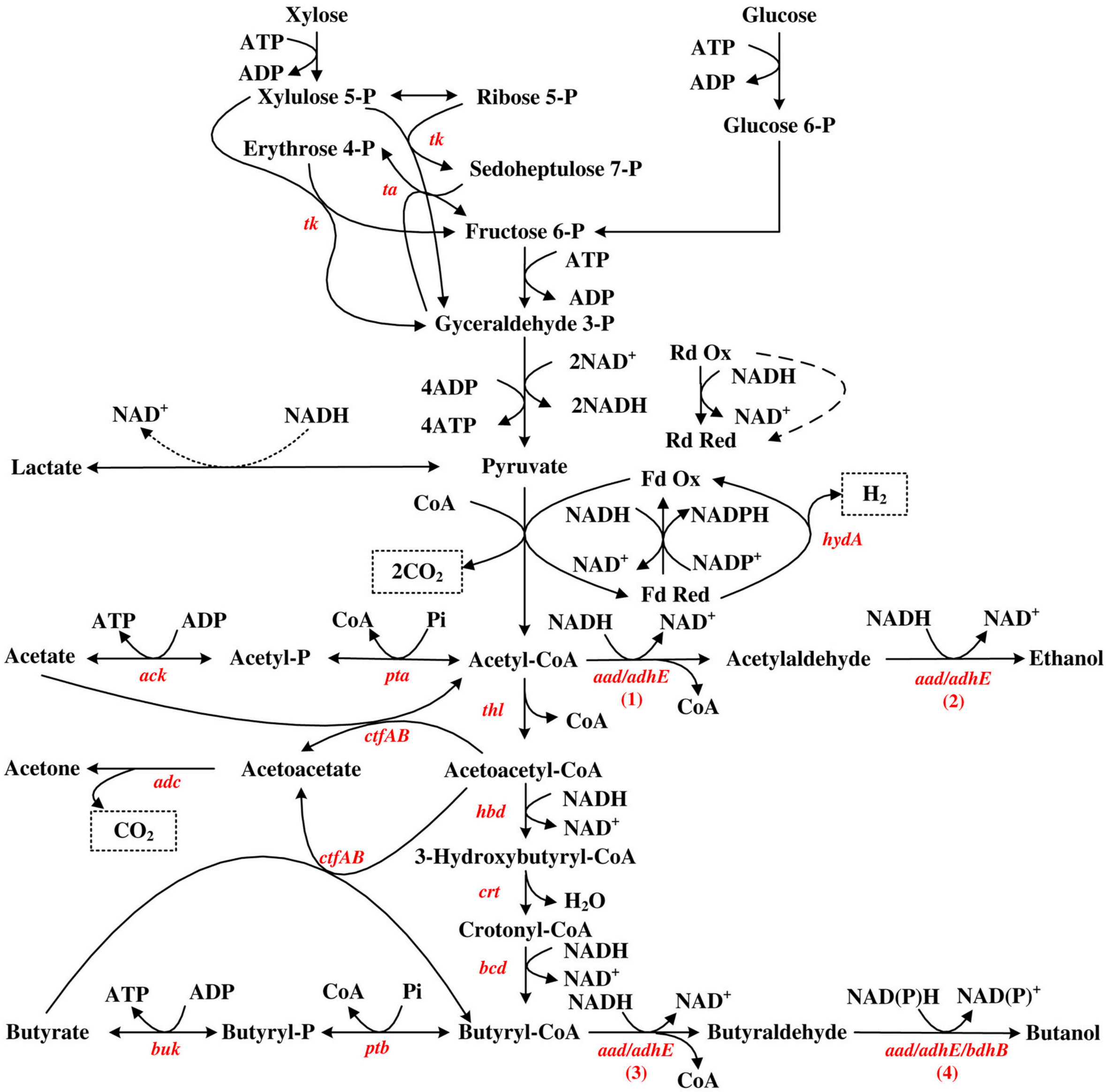

Fig. 5. Metabolic pathways in *Clostridium acetobutylicum* ATCC 824 with glucose and xylose. The genes are described in the pathways and their corresponding enzymes are as follows: tk, transketolase; ta, transaldolase; hydA, hydrogenase; pta, phosphotransacetylase; ack, acetate kinase; thl, thiolase; adc, acetoacetate decarboxylase; ctfAB, acetoacetylCoA: acetate/butyrate: CoA-transferase; hbd, 3-hydroxybutyryl-CoA dehydrogenase; crt, crotonase; bcd, butyryl-CoA dehydrogenase; buk, butyrate kinase; ptb, phosphotransbutyrylase; 1, acetaldehyde dehydrogenase; 2, ethanol dehydrogenase; 3, butyraldehyde dehydrogenase; and 4, butanol dehydrogenase. Source: Adapted and modified by the authors under the re-publish license number (5692200388513) from the study "Recent advances to improve fermentative butanol production: Genetic engineering and fermentation technology"[85].

8.4.2. Xanthan gum (XG)

XG is widely used as a thickener, stabilizer, and emulsifier in various industrial and food applications [50]. Date waste is utilized with XG, a polysaccharide produced by bacterial fermentation. Research enhances the waste material value by exploring XG production from date byproducts [118]. This trend aligns with the broader movement of seeking eco-friendly alternatives, such as XG, to synthetic compounds for various applications, including agriculture [119]. Moreover, the use of XG derived from microbial sources, such as date waste, has been deemed a sustainable and cost-effective approach [120]. XG and date waste biopolymers can transform waste materials into valuable products. XG, a food additive, can be produced from date waste, promoting the recycling and reuse of agricultural byproducts [121]. Research has examined the use of date palm waste for phosphate removal from water [122], and as an adsorbent for nitrate removal from wastewater [123]. Therefore, reducing waste for conservation and environmental benefits is highly recommended.

8.4.3. Poly 3-hydroxybutyrate (PHB)

PHB, a biodegradable thermoplastic synthesized by bacteria, shows promise for diverse applications because of its biodegradability. Desugared sugar beet molasses and date syrup were used as secondary carbon sources for PHB production in Bacillus megaterium [124]. *Lignocellulosic* biomass, biotechnological PHB waste, and alginate are sustainable bio-based chemical and polymer sources [95]. Other studies have focused on optimizing PHB production using unidentified bacterial strains and enhancing PHB's thermal properties of PHB through polymer blending [125]. Therefore, PHB, a biodegradable bacterial polymer, has versatile applications as a sustainable material.

8.5. Date waste and bio surfactant properties

The waste generated from the date fruit industry can be used as a source of carbon to produce bio-based chemicals and polymers [126]. Biosurfactants are surface-active molecules produced by microorganisms and have potential applications in various industries [127]. Date waste can be converted into industrial chemicals through fermentation and enzyme processing technologies, such as biofuels, biopolymers, OA, and enzymes [42]. *Bacillus subtilis* 20 B-produced biosurfactants using date molasses are less toxic and more biodegradable than chemical surfactants [128]. Date waste is processed into industrial chemicals and valuable products via fermentation and enzymes. Vermicompost enhances the nutritional, medicinal, and emulsifying qualities of date palm fruits [50]. Date palm waste can improve soil fertility and plant growth through composting or as a mushroom substrate [15]. Hence, date waste is beneficial when transforms into sustainable, valuable resources.

8.6. Organic acids (OA)

OA are found in many foods and industrial products, and contain carboxyl (–COOH) functional groups.

8.6.1. Citric acid (CA)

CA, a weak OA commonly found in citrus fruits, is frequently used as a food preservative and flavoring agent [129]. Fungi often produce this acid, which has a high commercial output of 98.42 g/L in media containing date syrup [56]. *Aspergillus* sp. *mutants* and *Candida lipolytica* can produce CA and gluconic acid via fermentation. Enhancing the process by incorporating crosslinking agents, whey, or other additives into a data syrup-enriched medium is possible [21]. Annually, 1.4 million tons of CA is produced, making it a widely produced OA classified as essential, primarily produced by *Aspergillus* and *Penicillium* spp [19]. *Trichoderma harzianum* PWN6 produces CA. The study tested pretreatment with dilute OA and CA.

Bueno et al. studied the molecular structure of xanthan hydrogel films with and without CA using a casting technique at 45 °C overnight [130]. Tartaric acid, oxalic acid, and CA were used as pre-treatments. Methanol and tricalcium phosphate were added to 20 % molasses in a whey culture of *Aspergillus niger* ATCC 6275 to enhance CA production, yielding 32.4 g/L [131]. Thus, improved xanthan gels and CA were produced using Aspergillus niger and citric acid.

One study found that CA had the lowest ethanol yield among tartaric, oxalic, and sulfuric acids [19]. GC-MS and ultra-performance liquid chromatography (UPLC) confirmed that CA was the only OA present at a concentration of 1.5 % [132]. *Aspergillus niger* has been used to produce CA from green olive processing wastewater and white grape pomace. The highest concentrations were achieved in media with methanol and tricalcium phosphate [133]. Therefore, CA production is the most efficient method for using specialized waste materials.

8.6.2. Lactic acid (LA)

LA is a naturally occurring OA commonly produced during bacterial fermentation [98]. Often used for food preservation, personal care products, and industrial applications [134]. LA bacteria ferment sugars from lignocellulose, produce LA, and can also produce both LA and acetic acids (AAs) when metabolizing carbohydrates. Date waste can be transformed into LA through enzymatic saccharification and fermentation. This process involves the use of date palm waste to produce fermentable sugars and LA, offering a cost-effective and environmentally friendly alternative [8]. Research has investigated the use of various waste streams, including food, sweet potato, and fish manure wastes, to produce LA via microbial fermentation [135–137]. Furthermore, agro-industrial wastes, such as mango peel waste and coconut water waste, have been explored for their potential in LA production, underscoring the potential of unconventional raw materials in bioprocesses [138,139]. Thus, the feasible conversion of waste streams into LA via bioconversion promotes sustainable waste management and production.

8.7. Date waste and amino acids profile

Date waste refers to uneaten or discarded dates that are consumed by humans. Amino acid profile refers to the specific types and amounts of amino acids in a sample. The amino acid composition of date waste can be assessed by analyzing the protein content of the waste. Research has revealed that date palm fruit seeds contain essential amino acids such as lysine, isoleucine, leucine, methionine, threonine, valine, and phenylalanine [140]. Add spirulina, a high-protein source of amino acids, to date nectar for better amino acid composition [141]. The date palm sap amino acid profile varies with collection time and tree sex [142]. Thus, date waste with a diverse array of amino acids is an appealing option for amino acid production.

8.7.1. Glutamic acid (GA)

GA, commonly utilized in the food, pharmaceutical, and cosmetic industries, is produced by fermenting date waste with *Corynebacterium glutamicum*, resulting in a concentration of 36.64 mg/mL [21]. Studies have demonstrated that date seeds contain substantial amounts of GA, making it a significant amino acid component [140]. Moreover, research has shown that *Corynebacterium glutamicum*, a *bacterium* capable of producing GA, can effectively utilize date waste for GA production [143, 144]. Therefore, date waste can serve as a valuable substrate for GA production through microbial fermentation processes.

GA can be generated from date waste using diverse techniques, such as fermentation employing bacteria, such as *Corynebacterium glutamicum* [144]. Zareian et al. demonstrated that bacteria can produce GA from glucose through Krebs cycle intermediates [145]. Moreover, specific bacterial strains, including *Lactococcus lactis*, have been identified to be suitable for GA production [146]. Therefore, microbial fermentation can convert date waste into a carbon source to produce GA.

8.8. Date waste and biomass production

Date waste is a by-product of date fruit processing and can be utilized for the production of various chemicals and bioproducts through fermentation [24]. Biomass production entails cultivating and harvesting organic materials as a sustainable energy source [105]. Date waste and syrup can be used to produce biomass and oxytetracycline using microorganisms, such as yeast, *lactobacilli*, and Streptococcus thermophilus. Previous studies have demonstrated the potential of this method [23]. Pourshoaib et al. noted the substantial amounts of waste generated from Kabkab dates and emphasized the economic potential of utilizing this waste for date syrup production [147]. Despite limited research, date fruit waste can be converted into bioenergy, chemicals, and materials through biorefining [148]. Therefore, the sustainable transformation of waste biomass into valuable products can be achieved using a biorefinery strategy.

Corynebacterium glutamicum can produce gamma-aminobutyric acid from date processing waste with a maximum yield of 8 mg/mL [149]. Global date fruit production has reached 8 million tons, with an estimated 10 % of waste generated from pits and spoiled fruits [15]. Ahmad et al. analyzed date palm waste for heavy metal content and energy potential [25]. These studies assessed the potential of date waste as a renewable energy source and its health impacts, with proper disposal being crucial for environmental prevention [20]. Thus, date waste offers value in terms of energy and health, underscoring the importance of efficient management.

8.8.1. Baker's yeast

Date syrup, a product derived from dates through water extraction, has been effectively used as a substrate to produce baker's yeast [150]. Additionally, waste from dates has been used in bakery yeast production by employing *Saccharomyces cerevisiae* strains [151]. Studies have also demonstrated that date palm waste can be utilized to produce bioethanol using Saccharomyces cerevisiae [62]. Thus, date waste can be converted into baker's yeast using date extract as a medium for yeast production.

Ali et al. successfully optimized baker's yeast production using date juice as a carbon source, resulting in significant amounts of yeast biomass [152,153]. The baker's yeast industry generates considerable waste, and researchers have attempted to treat wastewater from this industry to produce methane [154]. Moreover, baker's yeast production has been investigated using various waste products such as prickly pear waste, highlighting the potential for sustainable yeast production [155]. In general, the utilization of waste materials, such as date juice and other agricultural byproducts, shows potential for environmentally friendly and sustainable methods of baker's yeast production.

8.8.2. Probiotic lactobacilli (PLb)

PLb including *Lactobacillus casei*, is a beneficial bacterium that aids in improving gut health. These functional foods provide health and nutritional benefits to consumers [46]. Date fruit byproducts, including baker's yeast, *PLb*, and thermophilic dairy starters, have been investigated for their potential in biomass production [47]. Hence, *PLb* in foods can enhance nutrition and sustainability for functional food development.

Ethanol production influences the growth and metabolism of *lactobacilli* and *Saccharomyces cerevisiae*, which are common microorganisms found in fermented foods and beverages. This study evaluated the effects of Xylooligosaccharides (XOS) and fructooligosaccharides as probiotics and *Salmonella typhimurium* nutrients on digestive enzyme hydrolysis [23]. Enhanced microorganism interactions improve fermented food production and functional ingredient use. Probiotic XOS can be used as functional food additives, nutraceuticals, cosmetics, pharmaceuticals, or agricultural products [20]. Probiotic cells survived better in SGF, SIF, and yogurt media than free bacterial cells [99]. Hence, probiotic XOS shows remarkable potential for a wide range of industrial applications.

Probiotic fermentation produces short-chain fatty acids such as acetate, propionate, and butyrate, which provide metabolic energy and lower the pH of the host intestine [23]. Thus, precise prebiotic probiotic fermentation is vital to enhance gut health. Martín-Ríos et al. investigated using date fruit byproducts to create desired industrial chemicals or biomass, including probiotics [26]. Thus, Bacillus subtilis and cellulose derivatives play significant roles in both probiotic and industrial contexts.

8.9. Date waste and antibiotics

Microbial fermentation processes can convert date wastes into antibiotics. This waste is a suitable substrate for enzyme and OA production by various microorganisms [28,88]. Additionally, utilizing agro-industrial waste, including date waste, has the potential to produce antibiotics and other bioactive compounds [156]. Antibiotic residues in wastewater must be considered because of their potential to amplify antibiotic-resistant bacteria [157,158]. Therefore, effective waste stream management from antibiotic production and other sources is necessary to curb the spread of antibiotic resistance.

Fermentation and enzyme processing can convert date fruit waste into antibiotics [24]. Nanocellulose can also produce biofuels, biopolymers, biosurfactants, OA, and industrial enzymes [159]. However, composting date palm waste, pits, shrimp, and crab shells in a vessel system makes date palms suitable for mushroom cultivation [160]. Thus, date fruit waste is valuable for antibiotic production, environmental remediation, and sustainable farming.

Elsayed et al. examined the potential of bio-processing technology to utilize the byproducts and waste generated from processing date palm fruit [161]. This is aimed at maximizing the use of waste generated by the cultivation of crops such as date palms [15]. The substantial quantity of date palm fruit waste produced by the date processing sector raises environmental worries [47]. Despite extensive research on date fruit cultivation, utilization, and medicinal properties, few studies have explored their chemistry, pharmacology, and health benefits [133]. Thus, sustainable agriculture and environmental management can be enhanced by the bio-processing of date palm waste. The utilization of bio-processing technology for the conversion of date palm fruit byproducts and waste is currently being explored, and agriculture presents environmental and health research opportunities.

8.9.1. Date waste and bleomycin

Bleomycin, a cancer drug, harms the genetic material of cancer cells and causes them to die. A study used date syrup to produce bleomycin in *Streptomyces mobaraens* ATCC 15003 [31]. This approach has the potential to mitigate environmental issues caused by the accumulation of date palm fruit waste [162]. The medium composition was optimized for maximum bleomycin production using RSM [163]. Date syrup can replace conventional substrates to produce antibiotics, offering a sustainable solution for managing date waste and increasing the production of valuable antibiotics [164]. Utilizing bio-processing technology to transform date palm fruit processing byproducts and waste into valuable products offers a sustainable solution for managing agro-waste [62]. This method can address horticulture and field crop waste management issues [23]. To improve the conditions for submerged fermentation to produce XG from date waste [165]. Growing concerns over the environmental consequences of substantial date palm fruit waste generated by the data processing sector [60]. Despite extensive research on date palm cultivation and utilization, studies have explored the potential of date waste for the production of xanthan gum [165]. Valorizing agro-waste from horticulture and field crops, including date palms, is crucial for sustainable waste management [166]. Composting date palm waste in a vessel system effectively manages and utilizes date pits, shrimp shells, and crab shells [167]. Thus, reduced XG production promotes eco-friendly practices using date palm byproducts.

8.9.2. Date waste and oxytetracycline

The degradation of oxytetracycline (OTC) is influenced by various factors, including environmental conditions, microbial activity, and specific waste treatment processes [55,168–174]. Data waste has various industrial applications including the production of valuable compounds and antibiotics. *Streptomyces* spp. induces the formation of oxytetracycline [93]. The potential of date palm juice to produce oxytetracycline indicates its use in producing numerous chemicals [175]. Investigations have been conducted to produce oxytetracycline from date waste and byproducts, revealing various applications of date waste [176]. These findings indicate the potential for industrial applications of oxytetracycline and other valuable compounds in date waste [55]. Thus, oxytetracycline degradation depends on environmental factors, microbial activity, and waste treatment methods.

8.10. Date waste and enzymes

Enzymes can be produced from waste using waste as a substrate for microbial fermentation processes. Date waste has been found to be a suitable source to produce enzymes such as pectinase, α-amylase, invertase, and cellulase by various microorganisms [8,88,177].The composition of date waste provides a rich source of carbohydrates and nutrients that support the growth and enzyme production of microorganisms [88]. Studies have shown that enzymes such as pectinase can be produced at higher concentrations using date fruit waste as a substrate than other enzymes [177]. Additionally, optimization of enzymatic saccharification of date palm cellulosic wastes has been achieved using cellulases from specific microorganisms. Thus, proper management and utilization of date waste can contribute to sustainable enzyme production.

8.10.1. α-Amylase production

α-Amylase is an enzyme that collapses starch into smaller carbohydrates such as maltose and dextrins. It is used in various industrial applications, including beer brewing, textile manufacturing, and glucose syrup production [178]. Date waste can be utilized as a substrate to produce α-amylase through solid-state fermentation processes, illustrating the potential of using agricultural waste to efficiently produce valuable enzymes [179]. This strategy promotes sustainable waste management and demonstrates the versatility of date waste in enzyme production. This presents a promising path for transforming waste materials into valuable products via bioconversion. α-Amylase was found to be most stable at a pH of 6.0, and a temperature of 55 °C.

Solid-state fermentation methods can generate enzymes, including α-amylase, using date waste. Aslam et al. have shown that microorganisms, including *Bacillus licheniformis* KIBGE-IB3, can efficiently produce α-amylase by utilizing date fruit waste as a substrate [88]. Thus, utilizing date waste for α-amylase production offers a potential solution for sustainable bio-processing.

8.10.2. Pectinases production

Date waste can be transformed into valuable enzymes such as pectinase, which has numerous applications in various industries [184]. Waste can be converted into pectinase, an enzyme with multiple uses in different industries (139.2 g/L) and sucrose (78.6 g/L) content in the extract at 50°C and a flow rate of 17 ml/hr [20]. Pectinases can be produced efficiently using a variety of microorganisms from date waste. Research has demonstrated that *Aspergillus foetidus* can produce pectinase by utilizing fruit waste including cashew, banana, pineapple, and grape [180]. Bacillus licheniformis KIBGE-IB3 produces more pectinase from date fruit waste [88]. *Aspergillus niger* produces the most pectinase using orange peel and submerged fermentation [181]. The activity of pectinase is affected by fermentation time and metabolomics of Bacillus licheniformis DY2 [20]. Therefore, date waste efficiently yields pectinase, offering a sustainable solution.

To optimize date syrup extraction, pectinase and cellulase were used at various water-to-date ratios (2:1, 2.5:1, and 3:1). Industrially, endophytic fungi-derived enzymes are used to produce amylase, cellulase, laccase, lipase, protein, xylanase, pectinase, phytase, and phenoxidase. Pectinases play a significant role in various industries, accounting for 25 % of global enzyme sales [182]. *Bacillus subtilis* EFRL 01 can produce pectinase from date syrup and has potential for commercial production [85]. To enhance pectinase production, the suppression of fatty acid synthesis and incorporation of furfural and triclosan could be effective [19]. Commercial pectinase produce with 0.5 % mature orange fruits at 30 °C and pH 5.0, can be adapted to produce pectinase from date waste [183].Consequently, pectinase production using economical sources, such as date syrup, benefits diverse industries.

9. Date waste and enzymic processing

Date fruits and date molasses are vulnerable to microbial enzymes, making them ideal materials for fermentation [185]. Mussatto et al. investigatd fermentation and enzyme processing technologies to produce various industrial chemicals, including biofuels, biopolymers, biosurfactants, OA, antibiotics, and enzymes, by maximizing the utilization of date fruit processing byproducts and waste [186]. Processing date byproducts with enzymes reduces the environmental impact of daily disposal in date industries [51]. Kouhsar et al. studied the possibility of using waste date residue from the date processing industry as a substrate for enzyme production, with the goal of reducing environmental concerns and increasing the value of waste through the application of bioprocess technology [47]. Therefore, enzymatic processing can result in the production of several value-added products.

Date palm waste and food processing industries generate thousands of tons of discarded fruits daily, posing significant environmental issues [82]. Enzyme processing has been successfully studied for converting waste into value-added products [46]. Utilizing enzyme degradation to unlock lignocellulose in food processing waste. More research and improved methods needed for effective waste management [187]. Immature date fruits were treated with pectinase (0.1 %) for 120 min to optimize juice yield [95]. Therefore, date industries produce various products such as paste, syrup, dip, honey, jam, and vinegar.

9.1. Production of fructooligosaccharides

Date byproducts can create fructooligosaccharides (FOS) by replacing sugar with β-D-fructofuranosidase from *Aspergillus awamori* NBRC 4033 [188]. A 150 ml of water per 100 g of date byproducts was found to be the best for FOS synthesis, with a sucrose conversion rate of 53.26 %, FOS concentration of 123 g/L, and FOS productivity of 18.5 g/h/100 g [56]. Kouhsar et al. investigated the effects of XOS and fructooligosaccharides on digestive enzyme hydrolysis, as well as their potential as probiotic and nutrient sources for *Salmonella typhimurium* [47]. Thus, eco-friendly, health-promoting fructooligosaccharides from date byproducts.

The costs, emissions, and efficiency of holocellulose, lignin-derived bio-oil, and biochar were assessed [60]. Patel et al. examined the elements that affect the generation of fatty acids via anaerobic digestion of food waste [189]. Acidic treatments in biofuel production can lead to undesirable byproducts, but engineered microbes and biorefinery co-products can increase profitability [190]. Hence, the primary crop of Phoenix Dactylifera L accounts for 82 % of the country's fruit production.

9.2. Production of high-fructose syrup (HFS)

HFS is produced from corn starch, sugar cane, sugar beet, or other starchy materials through starch hydrolysis and enzymatic isomerization [191]. HFS is approximately 60 % sweeter than sucrose and 150 % sweeter than glucose, but only approximately 42 % can be obtained owing to limitations [133]. HFS production combines chromatography, membrane technology, and ionic liquids; however, these methods are costly [192]. Enzyme-based HFS production can be achieved by combining invertase from date palm fruits with an aqueous sucrose solution [31]. Enzyme immobilization on chitosan using glutaraldehyde allows efficient and sustained HFS production in a packed-bed reactor [193]. This process utilizes sucrose derived from aqueous date extracts, yielding 90 % of HFS production [192]. Therefore, palmitic enzymes and chitosan-immobilized invertases increase the HFS production efficiency and cost-effectiveness.

Date syrup is preferred over cane syrup, and pectinase/cellulase-treated Tamr fruit concentrate has potential for use in various food products [15]. The yeast species *Rhodotorula glutinis* can produce single-cell oil by utilizing data syrup. With a yield of 10 L of date syrup (Brix 10) per kg of low-quality date fruit, this process is efficient [194]. The yeast species *Rhodotorula glutinis* can efficiently produce single-cell oil using data syrup. This process yields 10 L of date syrup (Brix 10) per kg of low-quality date fruit [20]. The highest CA yield of 98.42 g per liter was obtained in media containing date syrup [195]. Compared to other food wastes, such as sweet sorghum syrup-derived ethanol and Jerusalem artichoke, juice-converted fructose syrup and ethanol via hydrolysis can serve as vehicle fuels in India [196]. LA can be prepared from sweet sorghum, date palm, and golden syrup [163]. Carrot pulp syrup showed the highest fatty acid productivity (1.90 g/L/h) and carotenoid productivity (9.79 μg/L/h) productivity at a total sugar concentration of 75 g/L [197]. Hence, date syrup is remarkable for its utility in culinary and biochemical applications.

Yadav et al. found that raising the C/N ratio of date syrup from to 20–70 can significantly increase *the lipid production of Rhodotorula glutinis* PTCC5256. A previous study also investigated L(+) LA production from alternative carbon sources, such as sweet sorghum and golden syrup [198]. Date syrup fermentation can yield fructose and ethanol in food and fuel markets [199]. Due to its high inverted sugar content, date syrup has a C/N ratio of 45 and contains 8 % total sugar and 0.7 % protein [200]. Oman's primary fruit crop, date palm (*Phoenix Dactylifera* L), accounts for 82 % of the country's fruit crop production [15]. Overall, this is how date syrup and pits affect Lactococcus lactis nisin production and growth.

Date syrup is a thick and sweet liquid that results from boiling and reducing juice extracted from ripe dates[201]. Widely used in Middle Eastern and North African cuisines, date syrup is a natural sweetener that is rich in sugar, vitamins, and minerals. It is an excellent alternative to sugar or honey in many recipes[202]. Diverse types of date syrup, including native, glucose-added, and $(NH_4)_2SO_4$-amended varieties, have been utilized for fermentation processes[203]. The date industry creates numerous products such as paste, dip, honey, jam, vinegar, and syrup. A proposal to transform byproducts into biohydrogen, biogas, and syrup in a sustainable manner[204]. Date syrup was made from subpar Fars, Jahrom date palms, and *Rhodotorula glutinis* yeast. A10 liters of low-quality date fruit with a Brix of ten was boiled, yielding 1 kg of date syrup [194]. Organoleptic assessment favors date syrup over cane syrup, suggesting the potential of concentrate date syrup in food product development using pectinase/cellulase[205]. Explaining the extraction of single-cell oil (SCO) from *Rhodotorula glutinis* PTCC5256 using low-grade data syrup.

Date syrup and date pits impacted the growth of *Lactococcus lactis*, leading to 10 L of date syrup per kg of low-quality date palm fruits[206]. *L. plantarum* QS3B20 carotenoid production increased with date syrup [21]. Supplementing the medium with date syrup increased CA production, reaching a concentration of 98.42 g/L[107]. Enzymatic treatment affects quality and composition[207]. Carbon sources, such as sweet sorghum, date palm, and golden syrup can be utilized to produce L (+) LA [208]. Saudi Arabian Reziz dates with high sugar content (83.51 % dry weight) were selected to make premium date syrup[209]. The disposal of data processing waste, such as pits, creates environmental issues[210]. Thus, altering the C/N ratio of date syrup can affect the production of SCO.

Date syrup with a higher C/N ratio (70:1) reduced cell biomass and increased SCO biosynthesis [194]. Lipid production significantly increased as the C/N ratio of date syrup increased, particularly between 20 and 70 % [211]. The study evaluated data syrup properties and revealed that it is a suitable alternative for fermentation in industrial production, including CA and SCO [212]. Date syrup, a sustainable alternative to synthetic media, provides a cost-effective solution for utilizing data processing waste [213]. Improving the C/N% of the date syrup medium and adding enzymes such as pectinase and cellulase can enhance the production of industrial products [107]. Thus, date syrup is a sustainable fermentation medium for waste utilization.

9.3. Date waste juice concentrate

Immature date fruits can be used to produce concentrated date juices by removing water using pectinase enzymes. This results in a more concentrated form of the date juice [205]. Date fruits were treated with 0.1 % pectinase for 120 min to optimize juice yield and evaluate the quality of the resulting juice concentrate [214]. Date palm fruits provide a range of products, including date juice concentrates, fermented date items, and date pastes, and they are often consumed raw as well [215]. *Rhizobium radiobacter* ATCC 6466 generated 22.83 g/L of Curdlan when using date palm juice byproducts in optimal medium [118]. Sugar cane juice and date juice concentrate treated with pectinase have been shown to be effective in producing butanol for up to six months, resulting in fresh and ready-to-drink beverages with excellent sensory qualities [105]. Despite the widespread use of date palm fruits, comprehensive studies have been conducted on their utilization and waste management [66]. The authors emphasized the need for novel approaches to produce superior fruit juice concentrates and noted the scarcity of studies on the therapeutic uses and health benefits of consuming dates [216]. Date fruits are known for their high nutritional value and are commonly used for human nutrition [217]. The increasing demand for date products has led to the study of various methods for date juice extraction and syrup production [218]. Agricultural waste products from date fruits, such as fallen fruits, date press cakes, and date pits, are commonly used as animal feed [42]. For example, Saudi Arabia is one of the world's major producers of dates, which are marketed globally as high-value confectioneries [219]. Date palm byproducts, including date juice and waste from processing, have been increasingly studied and used [216]. Date juice byproducts are processed using multiple methods to produce XG and ethanol. Pectinases have also been found to reduce date juice viscosity [220]. Overall, the sugar content of date juice can vary depending on the type of fruit, its ripeness, and the time it is harvested.

9.4. Research output and future trends

This comprehensive review focuses on the advances and future perspectives in the biotechnological bioconversion of date waste into valuable resources, emphasizing this process's economic and environmental benefits. These findings highlight the successful production of antioxidants, enzymes, and polysaccharides from date waste, as well as converting fossil-based plastics into bioplastics through bioconversion processes. Furthermore, this research underscores the potential of bioconversion processes to drive economic growth by developing new products. The implementation of sustainable waste management practices can be summarized as follows.

i. **Bioconversion of Date Waste**: The study focuses on transforming date waste into valuable resources, highlighting its economic and environmental advantages. Key outcomes include the production of antioxidants, enzymes, and polysaccharides and the conversion of fossil-based plastics into bioplastics via bioconversion processes [221].
ii. **Economic Growth and Sustainable Practices**: Bioconversion processes' potential to stimulate economic growth by developing new products and sustainable waste management practices has been illustrated [6,14]. The significance of human capital and agricultural growth and their correlation with economic prosperity are also emphasized. Optimization of bioconversion processes is posited as a pathway for economic development [11, 222].
iii. **Production of Bioactive Compounds**: This segment demonstrates the utilization of data byproducts for producing bioactive compounds and dietary fiber, advocating their application across various industries to create value-added products [7,223].
iv. **Future Trends in Bioconversion**: The section calls for intensified research and development efforts to maximize the potential of bioconversion. It focuses on refining processes, innovating products, and overcoming the challenges related to implementation and regulation, particularly in developing countries [8]. The integration of biotechnology into waste management and the exploration of its benefits are essential research directions. This encompasses advanced waste treatment methods that use artificial intelligence and machine learning [16]. The potential synergy between biotechnology and renewable energy technologies for producing clean energy from organic waste was also noted with the expectation of increased integration [224].
v. **Emphasis on Reducing Fruit Waste through Biotechnology**: Attention has shifted toward minimizing fruit waste, showcasing recent technological advancements, such as anaerobic digestion, composting, and pyrolysis. These methods transform organic waste into biofuels, fertilizers, and soil conditioners, benefiting agriculture, food processing, and healthcare [225,226].
vi. **Prospects for Biotechnological Research and Sustainable Solutions**: Future research should focus on developing more efficient and sustainable waste treatment techniques. The

application of artificial intelligence and machine learning to improve waste management efficiency has been highlighted [23, 227]. In addition, the growing use of biotechnology for generating clean energy from organic waste materials and the expected increase in renewable-resource-based bioplastics are discussed. These efforts aim to reduce the dependence on conventional plastics and mitigate their environmental impacts [227].

10. Limitations and future research direction

The limitations and future research directions of advances and perspectives in the biotechnological and bioconversion of date byproducts can be summarized as follows.

10.1. Limitations

i. **High cost:** Implementation of biotechnology-based waste management systems can be costly, which may hinder their widespread adoption. The high cost could be associated with the technology itself as well as the infrastructure required for its implementation. This limitation may restrict the accessibility of innovative waste management methods in certain industries or regions, thereby affecting their overall effectiveness.
ii. **Limited Awareness:** There is a lack of public awareness regarding biotechnology-based waste management technologies. This limited awareness can impede the acceptance and utilization of innovative waste management methods. Addressing this limitation is crucial for successful implementation and adoption of biotechnological waste management solutions.
iii. **Insufficient Capacity:** Existing waste management facilities may have insufficient capacity to handle increased volumes of waste. As the demand for date products increases, the waste generated from date processing may also increase, putting pressure on the existing waste management infrastructure. This limitation highlights the need for more efficient and sustainable waste treatment methods to effectively handle growing volumes of waste.

These limitations underscore the need for further research and development to address the challenges associated with the biotechnological and bioconversion of date byproducts. Overcoming these limitations is essential for the successful integration of biotechnology into waste management processes and realization of its potential benefits.

10.2. Future research directions

i. **Artificial Intelligence and Machine Learning**: Future research should focus on the development of more efficient and sustainable waste treatment methods using AI and machine learning (ML) techniques to optimize waste management processes and improve waste conversion efficiency. AI and ML can play crucial roles in enhancing the effectiveness of waste management systems by enabling predictive analytics, process optimization, and real-time monitoring, leading to more sustainable and cost-effective solutions.
ii. **Integration of Biotechnology and Renewable Energy Technologies**: The integration of biotechnology with renewable energy technologies such as photovoltaic systems are anticipated to grow, allowing the generation of clean energy from organic waste materials. Research in this area should focus on further developing the integration of biotechnology and renewable energy technologies to enable the production of clean energy from organic wastes. This could involve the exploration of innovative methods for bioenergy production, such as biofuel generation from date byproducts, to develop sustainable energy production solutions.
iii. **Development of Bioplastics**: Research should be conducted to develop more durable, biodegradable, and economically viable bioplastics. The use of bioplastics produced from renewable resources is likely to increase, thereby reducing dependence on conventional petroleum-based plastics and their associated environmental effects. Future research should focus on enhancing the properties of bioplastics derived from date byproducts, such as improving their mechanical strength, biodegradability, and cost-effectiveness, to promote their widespread adoption as sustainable alternatives to traditional plastics.
iv. **Public Awareness**: Increasing the public awareness of biotechnology-based waste management technologies and their benefits should be the focus of future research. Educating the public about the advantages of biotechnological and bioconversion methods for waste management is essential to their widespread acceptance and utilization. This could involve outreach programs, educational campaigns, and knowledge dissemination initiatives to inform the public about the environmental and economic benefits of innovative waste management technologies.

In summary, future research on the biotechnological and bioconversion of date byproducts should prioritize the development of more efficient and sustainable waste treatment methods using AI and ML, integration of biotechnology with renewable energy technologies, advancement of bioplastic technology, and promotion of public awareness of the benefits of biotechnology-based waste management.

11. Conclusion

This study explored the concept of bioconversion, which involves the transformation of waste materials into valuable products with the help of microorganisms. The focus is on date byproducts, which are converted into valuable bioactive compounds and nutrients, with applications in various industries. Recent studies have focused on the production of antioxidants, enzymes, and polysaccharides from date waste. The application of biotechnology is expected to boost the productivity and economic viability of bioconversion processes. This approach offers a sustainable solution to waste management and economic growth. This review analyzes the existing status of date waste bioconversion and explores the potential of future biotechnological innovations to generate valuable products. It discusses different bioconversion technologies, the products that can be produced, the economic and environmental benefits, and the challenges that must be overcome for their widespread adoption. Future research directions were also explored.

12. Declaration

The authors meticulously reviewed and revised the manuscript, assuming complete responsibility for its content. They also engaged professional proofreaders in refining grammar and sentence construction. Subsequently, a similarity assessment was performed using **iThenticate**, resulting in a **10 %** similarity score with no AI-related similarities. Additionally, all pertinent data, along with the similarity report, have been provided as supplementary files, adhering to established publication norms.

CRediT authorship contribution statement

Khalid Hamid Musa: Writing – review & editing, Writing – original draft, Supervision, Methodology, Formal analysis, Data curation, Conceptualization. **Ahmed A.M. Elnour:** Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Software, Project administration, Methodology, Investigation, Formal analysis, Data curation, Conceptualization, Dr.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jafr.2024.101145.

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