



FROM FRUIT WASTE TO FUNCTIONAL BIOCATALYSTS: A REVIEW OF BIO-ENZYME PRODUCTION, CHARACTERIZATION AND APPLICATIONS IN CIRCULAR BIOECONOMY

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Abstract: Fruit and vegetable waste contains many sugars, fiber, and nutrients. These can be used by microbes to make valuable industrial tools called enzymes. This review looks at how we can turn fruit waste into enzymes through fermentation. It discusses the best waste mixtures, microbes, and setups to use. We look at major enzymes like pectinases, cellulases, amylases, xylanases, proteases, and lipases, and how they are used in food, detergents, clothes, and cleaning the environment. We also explain the difference between crude homemade "bio-enzymes" and scientifically tested enzymes. Finally, we look at how to collect, stabilize, and reuse these enzymes safely. Turning fruit waste into enzymes reduces pollution and creates useful products, supporting green chemistry and a circular economy. However, we still need standard recipes, better testing, and cost reviews before using them on a large scale.

Keywords: Fruit waste; bio-enzyme; fermentation; enzymes; waste reuse.

1. Introduction

The fast growth of food processing and consumption creates huge amounts of fruit and vegetable waste every day. Things like peels, seeds, cores, and skins are thrown away during harvest, processing, and selling. Even though these materials are treated as trash, they contain a lot of sugars, fiber, proteins, and minerals. This makes them excellent raw materials for new products [1–3].

Fruit waste rots quickly because it has a lot of water and organic matter. When left untreated, it smells bad, creates greenhouse gases, and pollutes water. Throwing it away means we waste good resources. Today, scientists focus on waste reuse, which means turning trash into useful things like chemicals, fuels, and enzymes.

Microbes provide a great way to do this. Many bacteria and fungi can eat food waste to grow and create natural enzymes. This means fruit waste can act as cheap food for microbes.

Industrial enzymes are useful because they can speed up chemical reactions safely under mild

conditions. Enzymes like pectinases, cellulases, amylases, xylanases, proteases, and lipases are used heavily in the food, clothing, detergent, and paper industries [9–11].

Many people use the term "bio-enzyme" or "eco-enzyme" for crude, homemade fermented liquid made from fruit trash. Scientifically, however, this liquid is a complex mix of organic acids, sugars, and multiple enzymes. It is not the same as a pure, tested enzyme. Therefore, we must run laboratory tests to find out exactly how strong and safe these mixtures are before using them in factories.

2. Fruit Waste as a Renewable Feedstock

The exact mix of fruit waste changes depending on the type of fruit, how ripe it is, where it grew, and how it was processed. For example, fruit peels contain a lot of pectin, cellulose, and natural sugars. Pathak et al. showed that common peels like banana, orange, and jackfruit have great chemical traits for making new products. This proves that fruit trash should be treated as a valuable resource, not just garbage.



Table 1. Common fruit waste and what they can make

Fruit Waste Feedstock	Key Biochemical Components	Target Useful Products
Citrus / Orange peel	Pectin, sugars, essential oils	Pectinases, organic acids
Banana peel	Sugars, Fiber, minerals	Cellulases, amylases
Pineapple waste	Sugars, Fiber, proteins	Enzymes, fermented liquids
Mango peel	Pectin, Fiber, antioxidants	Pectinases, natural extracts
Apple pomace	Pectin, sugars, Fiber	Pectinases, organic acids

The biggest benefit of fruit waste is that it costs almost nothing. However, because the waste mixtures change often, microbe growth and enzyme amounts can change too. This means testing the waste first is very important.

3. Microbial Processing of Fruit Waste

Microbes are ideal for making enzymes because they grow fast and can make many types of tools. Fungi like *Aspergillus* and *Penicillium*, and bacteria like *Bacillus*, are the most popular choices for making industrial enzymes. The choice of microbe depends on the type of waste, the target enzyme, and the final use.

3.1 Submerged Fermentation

Submerged fermentation (SmF) means growing microbes in a large tank of liquid food. This setup makes it very easy to control the temperature, air, stirring, and pH. It is also easy to collect the final enzymes from the liquid. However, SmF uses a lot of water and leaves the enzymes very diluted, which increases energy costs during scale-up.

3.2 Solid-State Fermentation

Solid-state fermentation (SSF) means growing microbes directly on moist solid waste with no free liquid water. Fruit peels act as both food and a solid home for the microbes. SSF is very popular because it uses cheap waste, needs very little water, and creates highly concentrated enzymes [6–8]. Pandey described SSF as a vital tool for making industrial enzymes, and modern factories still use it today.

4. Microbial Enzyme Biosynthesis

Microbes make enzymes based on their regular growth habits. Fungi are perfect for solid waste because their root-like structures can spread across solid surfaces easily. Bacteria grow much faster and finish the job in less time.

Enzyme production can happen naturally or can be triggered by specific triggers. The chemicals inside the waste can trigger the microbe to make a specific enzyme. For example, waste with a lot of pectin triggers pectinase production, while waste with a lot of fiber triggers cellulase production. Using natural waste removes the need for expensive laboratory sugars, though adding a little nitrogen or minerals can help the microbes make more enzymes.

5. Major Enzymes Made from Fruit Waste

5.1 Pectinases: These enzymes break down pectin. They are used to clarify fruit juices, process clothes, and treat waste. Amin et al. noted that fruit waste is perfect for making pectinase because fruit skins are naturally full of pectin.

5.2 Cellulases: These enzymes break down tough plant fibers. They are used in laundry detergents, clothing finishes, and biorefineries to turn plant waste into sugars for biofuels.

5.3 Amylases: These enzymes break down starch into simple sugars. They are widely used in food processing, brewing, and household detergents.

5.4 Xylanases: These enzymes break down hemicellulose. They are used in paper mills,



baking, and animal feed.

5.5 Proteases: These enzymes break down proteins. They are one of the most sold enzyme groups, used primarily in laundry detergents

and leather tanning.

5.6 Lipases: These enzymes break down fats and oils. They are used in food making, biodiesel production, and cleaning up oil spills.

Table 2. Main enzyme groups and how they are used

Enzyme	What it Breaks Down	Common Uses
Pectinase	Pectin	Clearing juices, treating fabrics
Cellulase	Plant fiber (Cellulose)	Making biofuels, processing clothes
Amylase	Starch	Food making, laundry detergents
Xylanase	Hemicellulose	Paper bleaching, baking
Protease	Proteins	Stain removal, leather softening
Lipase	Fats and Oils	Food processing, eco-diesel

6. Factors Affecting Enzyme Production

Making enzymes efficiently depends on a few key things working together:

- **Waste Amount and Size:** Giving the microbes enough food helps them make more enzymes, but too much waste can block airflow. Grinding the waste into smaller pieces gives the microbes more surface area to work on, but pieces that are too small can pack together tightly and choke the microbes.
- **Water Content:** This is critical for solid setups. Too little water stops the microbes from growing, while too much water fills up the air holes and blocks oxygen.
- **pH and Temperature:** These control how well the microbes grow. The best temperature for making an enzyme is often different from the temperature where the enzyme works best.
- **Air and Stirring:** These keep oxygen flowing, which is very important when scaling up to large factory tanks.

7. Characterization of Fruit-Waste-Derived Biocatalysts

We must run laboratory tests to find out the exact quality and function of any fermented liquid. You cannot judge enzyme strength just by looking at the color or smelling the liquid. A real test program must measure: pH, sugar levels, total acidity, protein amounts, specific

enzyme strength, heat stability, and storage shelf-life. Because crude liquids contain a complex mix of acids, microbes, and enzymes, the term "bio-enzyme" must always be backed up by real laboratory numbers.

8. Enzyme Recovery and Downstream Processing

After fermentation, you must separate the liquid enzymes from the leftover solid waste and microbe cells using filtration or spinning tools. You can concentrate the liquid further by using special salts (like ammonium sulfate) or fine filtering membranes. For expensive medical uses, you need complex purification tools. However, because pure cleaning is very costly, factories prefer using partially purified crude extracts for cheap uses like detergents or waste treatment.

9. Enzyme Immobilization

Immobilization means trapping an enzyme on a solid support so it stays stable and can be reused. This can be done by sticking the enzyme to a surface, locking it inside a gel, or wrapping it in a tiny capsule. This process helps the enzyme withstand heat and allows factories to use it over and over again in continuous setups. Sirisha et al. reviewed these methods and showed that natural materials like chitosan and cellulose make excellent, safe



holders for enzymes. This is a great way to make waste-derived enzymes cheaper to use.

10. Applications of Fruit-Waste-Derived Biocatalysts

10.1 Food and Drinks: Pectinases and amylases clear up cloudy juices, improve liquid extraction, and help in beer brewing.

10.2 Clothes and Paper: Cellulases and xylanases soften fabrics, polish clothes, and help bleach paper pulp without using harsh industrial chemicals.

10.3 Detergents: Proteases, amylases, and lipases are mixed into laundry detergents to remove tough protein, starch, and grease stains easily in cold water.

10.4 Environment and Fuels: Cellulases break down tough agricultural waste into simple sugars for making eco-ethanol, while lipases clean up oily industrial wastewater.

11. Green Chemistry and Circular Bioeconomy

Turning fruit trash into useful enzymes matches the main goals of green chemistry: preventing waste, using renewable materials, and using safe catalysts. Instead of throwing peels into landfills where they cause pollution, fermentation saves their biological value. A smart strategy is cascading reuse: extracting valuable essential oils from the fresh peels first, and then fermenting the leftover solids to make enzymes. This maximizes resource efficiency and lowers overall costs.

12. Conclusion

Fruit processing waste serves as an excellent, cheap raw material for making important industrial enzymes like pectinases, cellulases, and proteases. This approach successfully turns environmental waste into useful biological tools, supporting green chemistry and a circular economy. However, turning these crude liquids into real commercial products requires strict standard recipes. The term "bio-enzyme" must be backed up by real laboratory tests, steady processing habits, and clear cost reviews to build a sustainable, waste-free industrial future.

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