A Comprehensive Literature Review on Production of Acetic Acid from Various Fruit Sources

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***Abstract*—Fruit vinegar has gained popularity as one of the healthy drinks containing different bioactive compounds beneficial for human health. This review has been composed with the characterization of different fruit vinegars, their production processes, biological activities, and their impact on sustainable development. There are various phytochemical compounds present in fruit vinegars such as polyphenolic acids, tetramethylpyrazine, organic acids, and melanoidins. The most abundant organic acid present in all types of fruit vinegar is acetic acid which can prevent diabetes, hypertension, oxidative stress, obesity, inflammation, as well as can boost immunity by its remarkable antioxidant ability if administered orally on a daily basis at a particular dose as suggested by the physician. However, the quality of vinegar and its health benefits can be influenced by its production techniques.**

***Index Terms*—Fruit sources, Fermentation, Acetic acid, Food processing, Sustainability, Waste management**

I. INTRODUCTION

Vinegar is generally produced through alcoholic and acetic fermentation using various sugar containing starch materials such as fruit musts, cider, malted barley, or pure alcohol. Different fermentation processes which were used earlier for vinegar production include Orleans method, trickling generator method and submerged culture method. Now-a-days, only trickling generator method and submerged culture method are used for commercial production of vinegar. It has direct and indirect applications in several chemical sectors including food, pharma, chemical, textile, polymer, medicinal, and cosmetics [1].

The concept of vinegar is not a new one, its applications were also there 10,000 years ago (Vinegar Institute 2005). For around 5000 years, people used to manufacture and sell different types of vinegar prepared with fruits, honey and malt. In 1814, Berzelios first performed the complete analysis of acetic acid or vinegar and in 1921, Dobereiner finally established that the acetic acid and water are produced by the oxidation of alcohol [2].

Acetic acid, the main flavoring and antibacterial ingredient in vinegar, can be produced in a four-step reaction process as demonstrated below [3]:

I. Starch breaks down into simple sugars through enzymatic action by amylase.

$$(C_6H_{10}O_5)_n + nH_2O \rightarrow nC_6H_{12}O_6$$

II. Anaerobic fermentation of sugar by *Saccharomyces cerevisiae* for production of ethanol.

$$C_6H_{12}O_6 \rightarrow 2C_2H_5OH + 2CO_2$$

III. Ethanol undergoes oxidation to form acetaldehyde and then acetaldehyde reacts with water to produce hydrated acetaldehyde.

$$CH_3CH_2OH + [O] \rightarrow CH_3CHO + H_2O$$
$$CH_3CHO + H_2O \rightarrow CH_3CH(OH)_2$$

IV. Conversion of hydrated acetaldehyde to acetic acid by aldehyde dehydrogenase.

$$CH_3CH(OH)_2 + (O) \rightarrow CH_3COOH + H_2O$$

The final processing steps involved in vinegar production include filtration, clarification, maturation and pasteurization at 74°C. It has been observed that around 40% acetic acid can be produced using fermentation method [4].

Vinegars can be mainly of two types i.e. natural or brewed which can be produced by alcoholic and acetic fermentation process and synthetic which does not involve any fermentation process but prepared by diluting acetic acid to required strength [5].

Fruits containing fermentable sugars that can be used for the production of vinegar include apple (apple cider vinegar), grapes (wine or grape vinegar), orange, pear, pineapple, berries, banana etc. Additional sugar can also be added to increase the sugar content of fruit

vinegar. Besides, it can also utilize fruit surpluses and imperfect fruits which are rejected by fruit processing industries and thus reduces the negative environmental impact generated from wastes [1].

In this review article, we are going to discuss about different types of fruit vinegar, their production processes, biological activities and their impact on sustainable development.

II. CLASSIFICATION OF FRUIT VINEGAR

There are mainly three types of fruit vinegar currently available in market such as

Fermented Fruit Vinegar: It is produced by the two-step fermentation process. At first, fruit juice is fermented by yeast for production of alcohol and then in the second step, alcohol is fermented by acetic acid bacteria for production of acetic acid or vinegar. Examples: apple cider vinegar, pineapple vinegar, grape vinegar, mango vinegar, and pear vinegar [6].

Infused Fruit Vinegar: It is prepared by adding the extracts of some herbal ingredients or fruits or spices in fermented vinegar to provide a characteristic flavor. Examples: Raspberry infused vinegar, strawberry balsamic vinegar, blueberry vinegar, and lemon vinegar [7].

Blended Fruit Vinegar*:* It is developed by combining different fruit vinegars and then diluting the mixture slightly with water. It is less acidic and more flavorful. Examples: strawberry balsamic vinegar, blueberry apple cider vinegar, peach raspberry vinegar, and pineapple coconut vinegar [8].

III. PHYSICOCHEMICAL CHARACTERISTICS OF FRUIT VINEGARS:

The physicochemical properties of different fruit vinegars in terms of acidity, pH, color absorbance, and electrical conductivity are summarized in Table 1.

Table 1: Range Values of Different Physicochemical Characteristics of Fruit Vinegars

Fruit Vinegar	pH	Total Soluble Solid (TSS) (^{0}B)	Acidity Titrable (%)	Reference
Apple cider vinegar	2.84 ± 0.04	2.15	2.56 ± 0.14	[9], [10]
Grape vinegar	2.36-3.00	6.13±0.79	4.20 ± 0.18	[11]
Lemon vinegar	2-3	6.5	4.34 ± 0.07	[12], [13], [14]
Balsamic vinegar	2.83 ± 0.02	18.2	5.53 ± 0.49	[15], [16]
Pineapple vinegar	2.97 ± 0.23	13.07 ± 0.12	6.5%	[17], [18]
Mango vinegar	4.02 ± 0.10	22	6.12 ± 0.14	[19], [20], [21]
Pear vinegar	3.17-3.43	8.5	4.01-5.05	[22], [23]
Blueberry vinegar	2.63-2.98	13.02 ± 0.26	1.65-5.72	[24], [25]
Coconut vinegar	2.0-3.5	10	2-2.5	[26], [27]
Raspberry vinegar	3.30	5.50	6.82 ± 0.06	[28]

Fruit vinegars are also rich in various bioactive compounds such as polyphenols (gallic acid, vanillic acid, protocatechuic acid, syringic acid, caffeic acid, chlorogenic acid, *p*-coumaric acid, and ferulic acid), flavonoids (catechin and epicatechin) and several organic acids (lactic acid, tartaric acid, succinic acid, malic acid, and citric acid) [29] [30]. These bioactive compounds play an important role in the prevention and treatment of different human illness [14].

IV. MARKET ASPECT OF FRUIT VINEGAR

The size of global fruit vinegar market which was valued at USD 6.85 billion in 2023, is expected to reach USD 8.55 billion by 2030 by growing at a CAGR of 3.3%. [31] Key trends driving the market include various nutritional benefits of fruit vinegars, their innovative flavors, and versatile uses beyond culinary applications. The fruit vinegars providing major sales in global market by contributing characteristic flavors and nutritional properties to the finished product include apple cider vinegar, raspberry vinegar, pomegranate vinegar, blueberry vinegar and

mango vinegar [32]. Bragg Live Food Products, Australian Vinegar, Vitacost, Acetificio Marcello De Nigris, Mizkan Group, and ACETUM SRL are some of the top companies in global fruit vinegar market [31].

The Asia Pacific region is expected to share the major portion of the global fruit vinegar market during the projection period of 2024-2030 due to the increasing concern of consumers for intake of healthy products and production of fruit vinegars with new and unique flavors by the leading producers in Asia Pacific countries. The fruit vinegar market of North America and Europe are also expected to observe a significant rise during this period due to the high demand of consumers for improved and processed food, increased culinary applications of vinegar and rising consumer knowledge of healthy eating habits [33].

The fruit vinegar market in India is also predicted to grow at a CAGR of 7.1% (approximately) during 2024-2032 due to the growing demand for healthy food products, increasing health awareness among consumers, and rising disposable income [34]. Some key players of Indian fruit vinegar market are Mother Dairy Fruit & Vegetable Pvt Ltd., Dabur India Ltd., Patanjali Ayurved Limited., Nourish Organics Pvt Ltd., Everest Spices Private Limited, Oswal Agro Mills Ltd., and KisanVeer Foods Pvt Ltd [35].

Although global fruit vinegar market may face several challenges such as overconsumption of fruit vinegar which can lead to tooth decay, nausea and low potassium levels, maintaining consistent and pocket-friendly price of the product, and high chances of competition due to availability of substitutes [32][36].

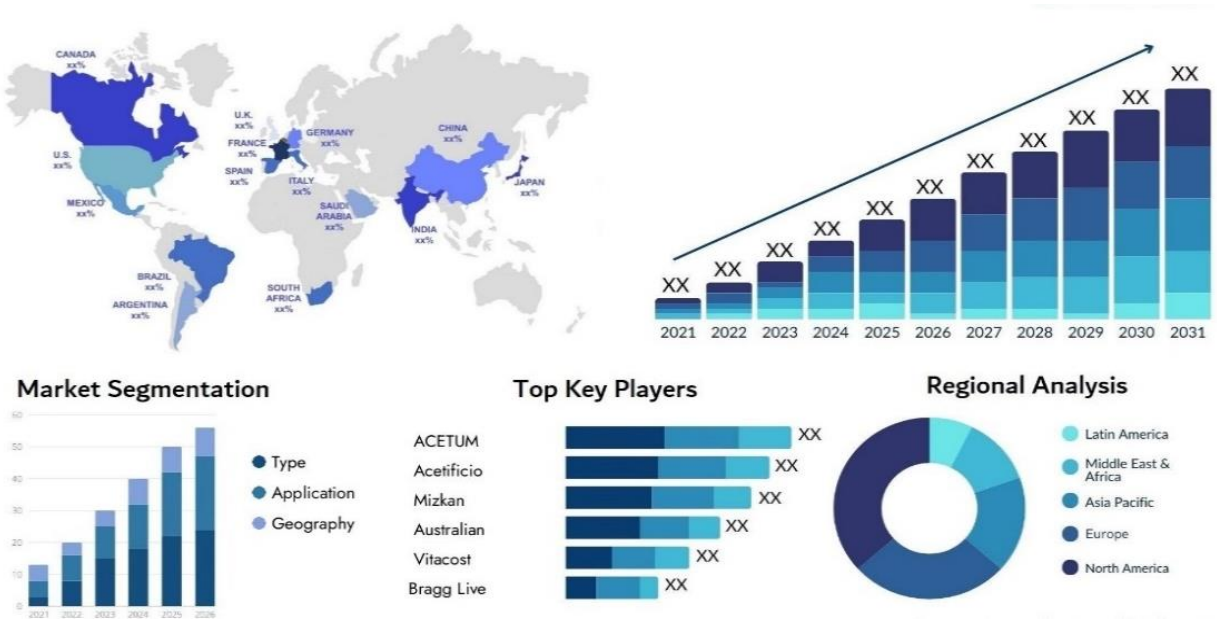

Figure 1: Fruit Vinegar Market Size and Scope [31]

V. METHODS FOR PRODUCTION OF FRUIT VINEGAR:

The three methods used for large-scale production of fruit vinegars include Orleans method or slow method, trickling generator or quick method and submerged fermentation method. Now-a-days, the last two methods are most widely used in industries.

A. Orleans Method or Slow Method:

It is the oldest method for production of pure and fine quality wine vinegar. In this method, 3/4th of the total volume (approximately 200 liter) of wood barrels are filled with alcohol containing liquid, such as wine or fermented fruit juice and several holes (covered with fine mesh) are created at the end of barrels above the liquid surface. Then a small amount of fresh vinegar (approximately 20-25%) is added to the wine to initiate the fermentation process as it helps to maintain the optimum pH and also acts as an inoculum of acetic acid bacteria. Later on, the acetic acid bacteria grow and create a thick slime layer on top of the liquid and it is fermented for 1-3 months at 70-85^{0}F for production of vinegar. After this time, 10-20% of the

vinegar may be drawn on a weekly basis for processing and an equal amount of liquid medium is added every time to continue the production process. The withdrawal and replenishment should be done from the bottom of the barrel so that the slime layer would not get disturbed [37] [38]. Although this method has several disadvantages such as

I. It is comparatively slower than other methods, taking so long time for vinegar production [37].
II. The bacteria come in contact with air and substrate only at the surface [38].
III. The process yields only 75-85% of the theoretical amount [37].

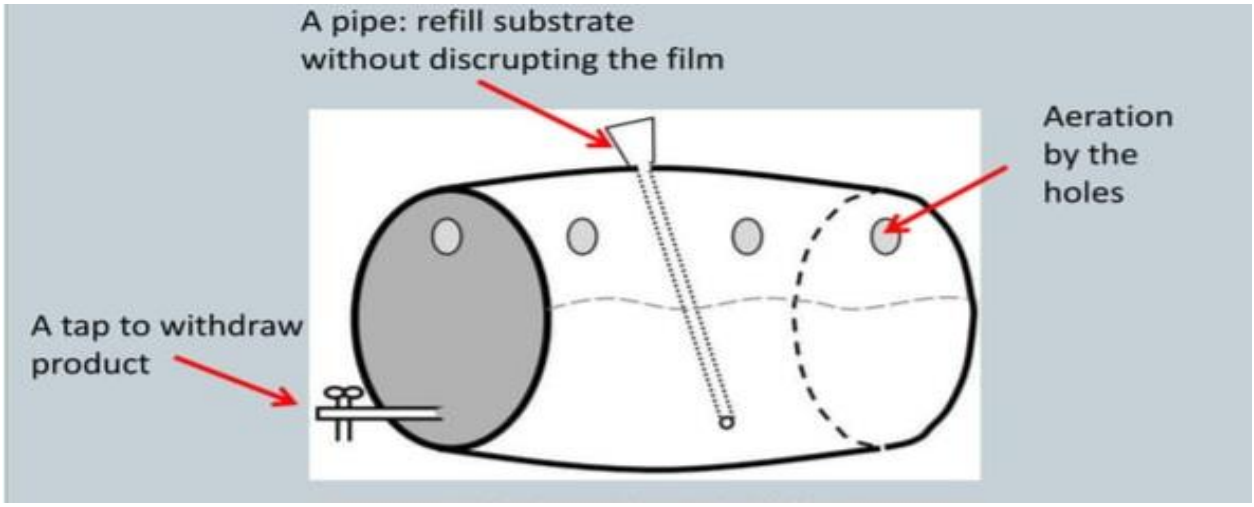

Figure 2: Bioreactor in Orleans Method [39]

B. Trickling Generator Method or Quick Method:
Trickling generator consists of a tall column filled with non-compacting material (coke or wood shaving charcoal) that provides a large surface area for the growth of acetic acid bacteria. The bottom of the column is fed with a continuous flow of alcohol-containing liquid, such as wine or fermented fruit juice, introduced into the column using a pump. Acetobacter bacteria naturally present or inoculated into the column oxidize the ethanol (alcohol) present in the incoming liquid into acetic acid (vinegar). This oxidation process occurs aerobically that means it requires oxygen which is supplied by allowing the oxygen-enriched air to flow counter currently to the alcohol-containing liquid within the column. The oxygen diffuses into the liquid and facilitates the growth of acetobacter, ensuring continuous conversion of alcohol to acetic acid. The process takes around 3 to 7 days to complete and during this fermentation process an optimum temperature of 30-32^{0}C is maintained [37] [38] [40]. This process has several advantages such as [38] [40]
I. It allows continuous production of vinegar without the need for batch processing.
II. The method can be scaled up to industrial levels by increasing the size or number of generator columns.
III. The large surface area provided by the packing material promotes high conversion rate of alcohol to acetic acid.

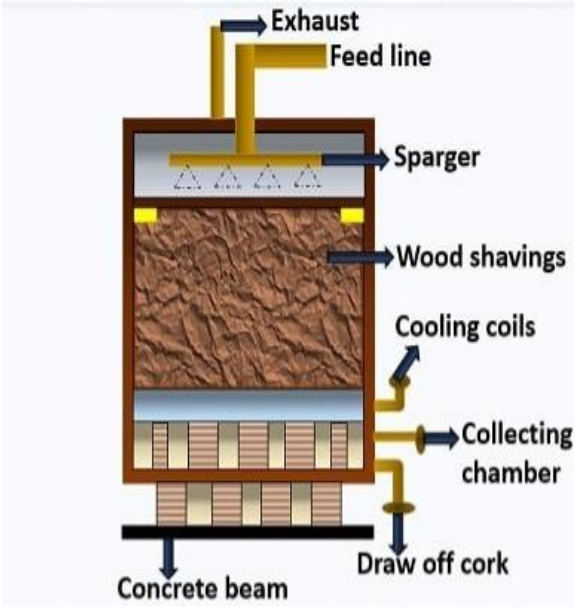

Figure 3: Trickling Generator [41]

C. Submerged Fermentation Method:

The process starts with the preparation of a suitable inoculum which involves growing a culture of acetic acid bacteria in a growth medium (typically consists of a carbon source (often ethanol or fermented fruit juice), nitrogen source (such as ammonium salts or yeast extract) and minerals) to ensure a high concentration of active bacteria. The fermentation tank used in this process is typically a sterilized large vessel, designed to hold the liquid medium where the bacteria will grow and produce vinegar. The tank is also maintained under controlled temperature (usually around 25-30°C), pH, and aeration to ensure optimal conditions for vinegar production. During the fermentation process, acetobacter bacteria metabolize the ethanol present in the fermentation medium and produce acetic acid and water as byproducts. Once the desired level of acetic acid concentration is achieved (typically when the acetic acid content is around 4-8% for vinegar), the fermentation process is halted and the fermented liquid is processed to ensure quality and stability before packaging [37] [38] [42].

Submerged fermentation is usually favored for its ability to produce large volumes of vinegar efficiently (90-98% of alcohol gets converted to acetic acid) and consistently. It is highly used in commercial production of fruit vinegar due to its scalability and control over fermentation conditions, which helps to maintain product quality and consistency [42].

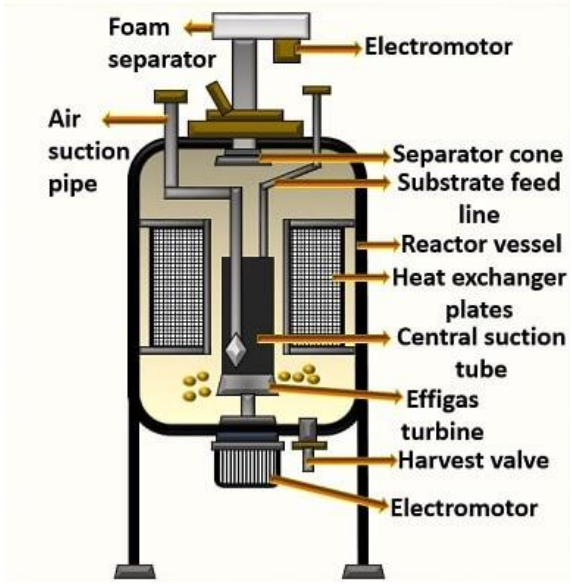

Figure 4: Submerged Fermenter [41]

VI. PROCESSING OF FRUIT VINEGAR

The final processing steps of fruit vinegar, which ensure that the product is of high quality, safe for consumption, and has a stable shelf life, typically involve the following stages:

- Filtration*:* After fermentation, the vinegar is filtered using coarse filters (for larger particles) and fine filters or membranes (for smaller particles) to remove the remaining solid particles, yeast, or bacteria. This step ensures clarity and stability of fruit vinegar [43].
- Pasteurization: To ensure stability and safety of the vinegar, pasteurization is carried out, which involves heating the vinegar to a specific temperature for a set amount of time to kill any remaining bacteria or yeast. This step helps in preventing further fermentation and spoilage [43].
- Clarification: Additional clarification step may be performed if necessary. This involves adding clarifying agents that help in settling out any remaining particles and after settling, the clear liquid is separated from the sediment [44].
- Maturation: Some fruit vinegars get benefit from aging, which enhances their flavor profile. It is done in non-reactive containers, such as glass or stainless steel, and can last from a few months to several years depending on the desired characteristics [45].
- Blending: During production of a consistent product from batch to batch, blending vinegars of different batches might be necessary to achieve a uniform flavor and acidity. This ensures that the final product meets the desired specifications [46].
- After performing the above-mentioned steps, the vinegar is finally bottled, sealed, labeled, and packaged for distribution.

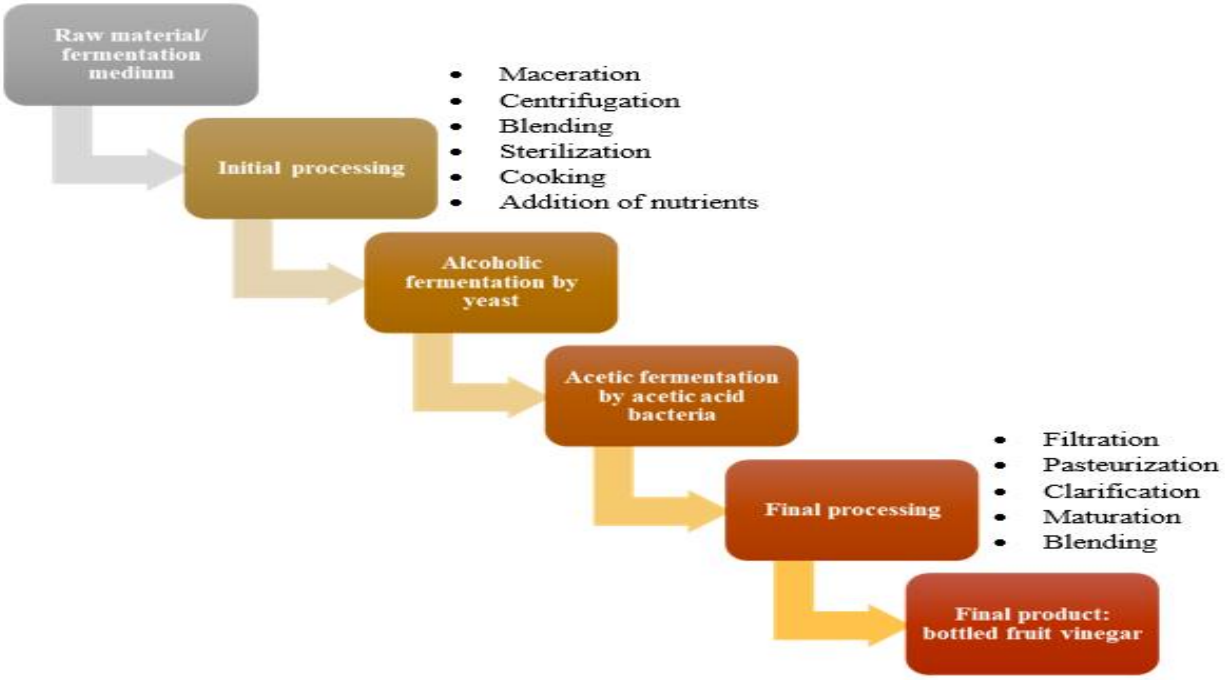

Figure 5: Schematic Representation of the Steps Involved in Fruit Vinegar Production [47]

VII. BIOLOGICAL ACTIVITIES OF FRUIT VINEGAR:

- Fruit vinegar contains huge amount of various bioactive compounds which are positively counteracting against numerous diseases such as
- *Antihypertensive Effect:* The potential antihypertensive effects of fruit vinegar involve several mechanisms such as:
- *Vasodilation:* Acetic acid has vasodilatory effects that means it can relax blood vessels and improve blood flow, which can help in lowering of blood pressure [48].
- *Antioxidant Effects:* Fruit vinegars contain huge number of polyphenols which have been shown to have beneficial effects on blood vessel function and blood pressure regulation by reducing oxidative stress and inflammation [49].
- *Reduction in Sodium Retention:* High sodium intake is a common cause of hypertension. Several animal studies have indicated that fruit vinegar can reduce the retention of sodium and water by the kidneys, thereby helping to lower blood pressure [50].
- Inhibition of Renin Activity*:* Acetic acid helps in lowering blood pressure by inhibiting the activity of Renin, an enzyme produced by the kidneys that plays a crucial role in regulating blood pressure by initiating a series of biochemical reactions that lead to the production of angiotensin II, a potent vasoconstrictor [51].
- Antiobesity Effect: The antiobesity effects of fruit vinegar are believed to be mediated through several mechanisms such as:
- Regulation of Metabolism*:* Acetic acid has been reported to increase AMP-activated protein kinase (AMPK) activity in cells to regulate cellular energy metabolism, promote fat burning and decrease fat storage [52].
- Impact on Digestion: Some studies have suggested that fruit vinegar slows down the rate at which food leaves the stomach, potentially leading to increased feelings of fullness and reduced appetite. This eventually results in lower calorie intake and subsequent weight loss or prevention of weight gain [53].
- Gut Microbiota Modulation: Fruit vinegar consumption also affects the composition of gut microbiota, which can in turn influence metabolism and weight regulation [54].
- *Improved Insulin Sensitivity:* There is some evidence that consumption of fruit vinegar can improve insulin sensitivity, which helps to reduce fat storage and promote the breakdown of fats,

which further helps to reduce the risk of developing obesity or aid in weight loss [55].

- Antidiabetic Effect*:* Fruit vinegar has been studied for its potential antidiabetic properties, which can be attributed to several mechanisms such as:
- Reduction in Blood Glucose Levels*:* Acetic acid can inhibit the activity of certain amylolytic enzymes, resulting in slower digestion and absorption of carbohydrates, leading to a lower postprandial blood glucose level [56].
- Increase in Glycogen Storage*:* Fruit vinegar can enhance glycogen storage in liver and muscles, reducing the amount of glucose circulating in the blood [57].
- *Improvement in Insulin Sensitivity:* The primary component of fruit vinegar, acetic acid, has been shown to enhance insulin sensitivity, allowing cells to utilize glucose more effectively and thus reducing blood glucose level [55].
- *Regulation of Gene Expression:* Consumption of fruit vinegar has been linked to the upregulation of genes involved in lipid metabolism and downregulation of genes associated with glucose production, contributing to the regulation of blood glucose level [58].
- Antioxidant Effect*:* The antioxidant activity of fruit vinegar is primarily due to the presence of different bioactive compounds that can neutralize free radicals and reduce oxidative stress. Here are the key mechanisms involved:
- Polyphenols and Flavonoids*:* Fruit vinegar contains large number of polyphenols and flavonoids, which are potent antioxidants. These compounds can donate electrons to free radicals, stabilizing them and preventing them from causing cellular damage [59].
- Enzymatic Antioxidants: Some fruit vinegars contain enzymes like superoxide dismutase (SOD), glutathione peroxidase, and catalase, which are crucial in breaking down harmful reactive oxygen species (ROS) [60].
- Synergistic Effects: The combination of different antioxidants in fruit vinegar can have a synergistic effect, enhancing the overall antioxidant capacity more than the sum of individual antioxidants [61].
- Phenolic Acids*:* Fruit vinegar is rich in several phenolic acids, such as gallic acid, caffeic acid, and chlorogenic acid, which contribute to its antioxidant capacity by neutralizing free radicals and chelating metal ions that catalyze oxidative reactions [10].

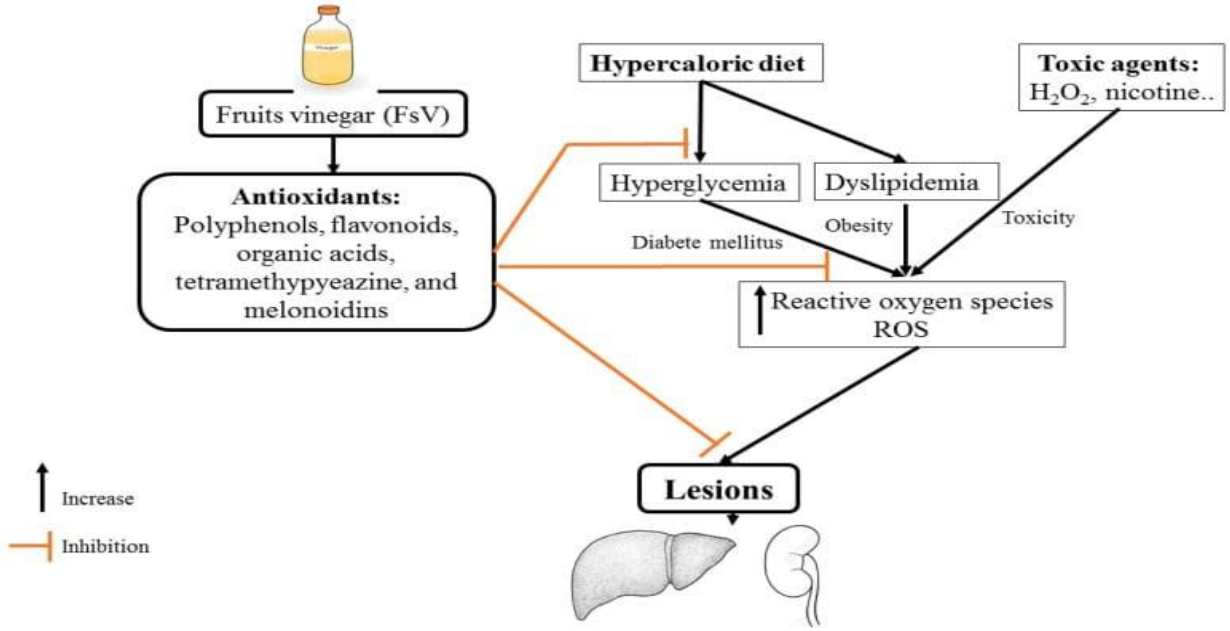

Figure 6: Antioxidant, Antihyperlipidemic and Antihyperglycemic Activity of Fruit Vinegar [14]

- Anti-inflammatory Effect: The anti-inflammatory activity of fruit vinegar can be attributed to

various bioactive compounds and their interactions with inflammatory pathways. Here are the key mechanisms involved:

- Polyphenols and Flavonoids*:* Fruit vinegar is rich in polyphenols and flavonoids, which can inhibit the production of pro-inflammatory cytokines and enzymes, such as interleukin-6 (IL-6), cyclooxygenase-2 (COX-2), and tumor necrosis factor-alpha (TNF-α) because of their strong anti-inflammatory properties [59].
- Acetic Acid: Acetic acid, the primary component of fruit vinegar, has been reported to inhibit the activation of nuclear factor-kappa B (NF-κB), a key transcription factor that regulates the inflammatory response [62].
- Suppression of Nitric Oxide (NO) Production: Excessive production of nitric oxide by inducible nitric oxide synthase (iNOS) is associated with inflammation. The bioactive Compounds present in fruit vinegar can inhibit iNOS activity, thereby reducing NO levels and inflammation [63].
- Modulation of Arachidonic Acid Pathway: The arachidonic acid pathway produces various pro-inflammatory eicosanoids. Fruit vinegar can inhibit enzymes like phospholipase A2 (PLA2) and COX-2, which are involved in this pathway, thereby reducing the synthesis of inflammatory mediators like prostaglandins and leukotrienes [64].

VIII. ADVERSE EFFECTS OF FRUIT VINEGAR CONSUMPTION

Fruit vinegar, which is generally considered to be safe and beneficial for human health, can have some potential side effects if consumed excessively such as:

- Digestive Issues: Overconsumption can lead to digestive discomfort, including nausea, bloating, and indigestion [65].
- Tooth Enamel Erosion: The acidity can erode tooth enamel over time, increasing the risk of cavities [66].
- Low Potassium Levels: Excessive intake can lead to lower potassium levels, affecting muscle function and heart health [67].
- Gastrointestinal Irritation*:* For those with a history of acid reflux, ulcers, or gastrointestinal issues, the acidity can exacerbate symptoms [68].

It's best to consume fruit vinegar in moderation and consult with a healthcare provider if one has any underlying health conditions or are taking medications. For safe consumption, a common recommendation is 1-2 tablespoons (15-30 ml) of vinegar in a large glass of water (240 ml) to be consumed 1-2 times per day before meals [69].

IX. WASTE TO WEALTH

The "waste to wealth" concept in fruit vinegar production revolves around utilizing fruit waste and by-products to create valuable products, promoting sustainability and reducing environmental impact. The sources of fruit waste that can be utilized for this purpose include fruit peels (citrus peels, apple skins, and other fruit rinds), pulp and juice leftovers during juice production, and overripe or unsold fruits [70]. There are several reasons associated with this initiative such as [71]

- Waste Reduction*:* Using fruit waste for production of vinegar significantly reduces the amount of organic waste that ends up in landfills. This helps to decrease landfill usage and associated methane gas emission, which is a potent greenhouse gas.
- Resource Efficiency: By converting waste into a valuable product, the efficiency of resource utilization is maximized. This supports the circular economy where waste is minimized, and materials are continuously repurposed.
- Food Security: Utilizing fruit waste helps to address the broader issue of food waste, contributing to food security. By making the most out of available resources, the pressure on food production systems is reduced.
- Nutrient Recovery: Fruit waste still contains valuable nutrients. Transforming it into vinegar ensures that these nutrients are not lost, but instead are preserved and consumed.
- Cost Savings: Using waste products reduces the cost of raw materials. Businesses can save money by utilizing what would otherwise be discarded.

Although there are some challenges like product consistency, adheration to food safety standards and

regulations, and consumer concern but by addressing these challenges through strategic planning and continuous improvement, the production of fruit vinegar from waste products can become a sustainable, economically viable, and scalable venture [72].

X. CONCLUSION

Though fruit vinegar is a tasty, useful cooking ingredient and it has several other applications but it is important to choose high-quality, organic fruit vinegars for the best flavor and potential health benefits.

The final physicochemical characteristics of fruit vinegar depends upon several factors such as the raw material and its treatment, type of microorganisms used in alcoholic and acetic fermentation and the type of acetification technique (submerged or surface treatment) employed. Although there are several scientific literature related to the commercial production of fruit vinegar but more research is still required about the use of thermotolerant bacteria which can carry out acetic fermentation at high temperature, optimal conditions for commercial production of fruit vinegar which can speed up the initiation of acetic fermentation, prevent pollution and decrease processing time, and use of innovative technologies such as pulsed electric fields, high hydrostatic pressure, microwaves, ultrasound and their effects in the production of fruit vinegars with high quality standards.

XI. ACKNOWLEDGEMENT

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REFERENCES

[1] Tan, S.C. (2005). Vinegar Fermentation. 1-3. https://ucfoodsafety.ucdavis.edu/sites/g/files/dgvnsk7366/files/inline-files/192137.pdf

[2] Sankpal, A. A. (2019b). An overview on types, medicinal uses and production of vinegar. Deleted Journal, 8(6), 1083–1087. https://www.thepharmajournal.com/archives/2019/vol8issue6/PartS/8-6-127-167.pdf

[3] John, R. (2021, March 29). Vinegar (acetic acid) production. SlideShare. https://www.slideshare.net/slideshow/vinegar-acetic-acid-production/245241502

[4] House, E. P. (2014, August 5). Optimization of process parameters for vinegar. SlideShare. https://www.slideshare.net/slideshow/optimization-of-process-parameters-for-vinegar/37668700

[5] Technology of Vinegar Production (n.d.). https://epgp.inflibnet.ac.in/epgpdata/uploads/epgp_content/food_technology/technology_of_fruits_and_vegetables/29.technology_of_vinegar_production/et/2860_et_m29.pdf

[6] Fenley, K., & Fenley, K. (2024, February 14). How to Make Vinegar from Scratch • Cultured Guru. Cultured Guru • Enrich Your Ecosystem. https://cultured.guru/blog/how-to-make-vinegar-from-scratch

[7] Flavored vinegar Definition | Law Insider. (n.d.). LawInsider.https://www.lawinsider.com/dictionary/flavored-vinegar

[8] Verster, J. (2016, August 14). Blended White Vinegar. Cooking up a Storm Culinary Experiences. https://www.cookingupastorm.co.za/recipes/blended-white-vinegar/

[9] Abdali, Y. E., Saghrouchni, H., Kara, M., Mssillou, I., Allali, A., Jardan, Y. a. B., Kafkas, N. E., El-Assri, E. M., Nafidi, H. A., Bourhia, M., Almaary, K. S., Eloutassi, N., & Bouia, A. (2023b). Exploring the Bioactive Compounds in Some Apple Vinegar Samples and Their Biological Activities. Plants, 12(22), 3850. https://doi.org/10.3390/plants12223850

[10] Budak, H. N. (2021). Alteration of Antioxidant Activity and Total Phenolic Content during the Eight-Week Fermentation of Apple Cider Vinegar. Horticultural Studies, 38(1), 39–45. https://doi.org/10.16882/hortis.882469

[11] Kang, M., Ha, J. H., & Lee, Y. (2020). Physicochemical properties, antioxidant activities

and sensory characteristics of commercial gape vinegars during long-term storage. Food Science and Technology, 40(4), 909–916. https://doi.org/10.1590/fst.25119

[12] Why does vinegar have a lower pH than lemon juice and lime juice? (n.d.). Quora. https://www.quora.com/Why-does-vinegar-have-a-lower-pH-than-lemon-juice-and-lime-juice

[13] Ou, Q., Zhao, J., Sun, Y., Zhao, Y., & Zhang, B. (2023). Utilization of Lemon Peel for the Production of Vinegar by a Combination of Alcoholic and Acetic Fermentations. Foods, 12(13), 2488. https://doi.org/10.3390/foods12132488

[14] Ousaaid, D., Mechchate, H., Laaroussi, H., Hano, C., Bakour, M., Ghouizi, A. E., Conte, R., Lyoussi, B., & Arabi, I. E. (2021f). Fruits Vinegar: Quality Characteristics, Phytochemistry, and Functionality. Molecules/Molecules Online/Molecules Annual, 27(1), 222. https://doi.org/10.3390/molecules27010222

[15] Lalou, S., Hatzidimitriou, E., Papadopoulou, M., Kontogianni, V. G., Tsiafoulis, C. G., Gerothanassis, I. P., & Tsimidou, M. Z. (2015). Beyond traditional balsamic vinegar: Compositional and sensorial characteristics of industrial balsamic vinegars and regulatory requirements. Journal of Food Composition and Analysis, 43, 175–184. https://doi.org/10.1016/j.jfca.2015.07.001

[16] Table 1. Observed colour, total soluble solid content, pH and total. . . (n.d.). ResearchGate. https://www.researchgate.net/figure/Observed-colour-total-soluble-solid-content-pH-and-total-titratable-acidity-of-wine_tbl1_240638823

[17] Wang, X. F., Hu, Y., Li, J. H., Zhang, L., Gong, X., & Hui, H. (2020). Analysis of the basic components and free amino acid composition of pineapple fruit vinegar. E3S Web of Conferences, 185, 04047. https://doi.org/10.1051/e3sconf/202018504047

[18] Boondaeng, A., Kasemsumran, S., Ngowsuwan, K., Vaithanomsat, P., Apiwatanapiwat, W., Trakunjae, C., Janchai, P., Jungtheerapanich, S., & Niyomvong, N. (2022). Comparison of the Chemical Properties of Pineapple Vinegar and Mixed Pineapple and Dragon Fruit Vinegar. Fermentation, 8(11), 597. https://doi.org/10.3390/fermentation8110597

[19] Adebayo-Oyetoro, A. O., Adenubi, E., Ogundipe, O. O., Bankole, B. O., & Adeyeye, S. a. O. (2017). Production and quality evaluation of vinegar from mango. Cogent Food & Agriculture, 3(1), 1278193. https://doi.org/10.1080/23311932.2016.1278193

[20] Boonsupa, W. (2019). Chemical properties, antioxidant activities and sensory evaluation of mango vinegar. International Journal of Agricultural Technology 15(2): 229-240. http://www.ijat-aatsea.com/pdf/v15_n2_2019_March/3_IJAT_15(2)_2019_Boonsupa,%20W..pdf

[21] Bouatenin, K. M. J., Kouamé, K. A., Gueu-Kehi, M. E., Djéni, N. T., & Djè, K. M. (2020). Organic production of vinegar from mango and papaya. Food Science & Nutrition, 9(1), 190–196. https://doi.org/10.1002/fsn3.1981

[22] Table 2. Comparison of pH, total acidity, sugar content and reducing. . . (n.d.). ResearchGate. https://www.researchgate.net/figure/Comparison-of-pH-total-acidity-sugar-content-and-reducing-sugar-content-of-commercial_tbl1_264137419#:~:text=The%20pH%20and%20total%20acidity,respectively%20(p%3C0.0)

[23] Ranganathan, A., Iftikhar, S., Tripathi, J., & Paroha, S. (2024). Production of Vinegar from Pear Juice and Comparative Analysis of its Quality with Apple Juice Vinegar. Advances in Research, 25(1), 117–125. https://doi.org/10.9734/air/2024/v25i11024

[24] 오현화, 장소원, 전현일, 정도연, 김영수, & 송근섭. (2017). 블루베리 농축식초 제조 및 이들의 항산화 및 항균 활성. Han'gug Sigpum Yeong'yang Gwahag Hoeji/Journal of the Korean Society of Food Science and Nutrition, 46(6), 695–702. https://doi.org/10.3746/jkfn.2017.46.6.695

[25] Titratable acidity, pH and total soluble solids of blueberry fruits, (n.d.). ResearchGate. https://www.researchgate.net/figure/Titratable-acidity-pH-and-total-soluble-solids-of-blueberry-fruits-blueberry-juice-and_tbl1_371999583

[26] SemiColonWeb. (n.d.). International Coconut Community.https://coconutcommunity.org/products-detail/vinegar

[27] PP, S. B., Ramarathinam, M., Pandiselvam, R., & Hebbar, K. B. (2018). Comparative evaluation of natural vinegar produced from mature coconut water and coconut inflorescence sap. ResearchGate.https://www.researchgate.net/publication/331330709_Comparative_evaluation_of_natural_vinegar_produced_from_mature_coconut_water_and_coconut_inflorescence_sap

[28] Silva, V., Mehrpour, G., Soares, V., Santo, D., Nunes, P., & Quintas, C. (2024). Quality and biological properties of vinegar processed from non-valorized fruits in Southern Portugal. Future Foods, 9, 100337. https://doi.org/10.1016/j.fufo.2024.100337

[29] Yildiz, E. (2023). Characterization of Fruit Vinegars via Bioactive and Organic Acid Profile Using Chemometrics. Foods, 12(20), 3769. https://doi.org/10.3390/foods12203769

[30] Liu, Q., Tang, G. Y., Zhao, C. N., Gan, R. Y., & Li, H. B. (2019). Antioxidant Activities, Phenolic Profiles, and Organic Acid Contents of Fruit Vinegars. Antioxidants, 8(4), 78. https://doi.org/10.3390/antiox8040078

[31] Kent, J. (2024b, March 19). Fruit Vinegar Market Size 2021 to 2023. Verified Market Reports® | Get Market Analysis and Research Reports.https://www.verifiedmarketreports.com/product/fruit-vinegar-market/

[32] Fruit Vinegar Market Size, Share Industry analysis, 2032 | MRFR. (n.d.). Market Research Future.https://www.marketresearchfuture.com/reports/fruit-vinegar-market-3759

[33] Fruit Vinegar Market Size & Share | Global Forecast Report 2028. (2023, February 15). https://www.researchnester.com/reports/fruit-vinegar-market/2762

[34] India Vinegar Market: Market Size, Forecast, Insights, Segmentation, and Competitive Landscape with Impact of COVID-19 & Russia-Ukraine.(n.d.).https://www.asdreports.com/market-research-report-655615/india-vinegar-market-market-size-forecast-insights-segmentation-competitive-landscape

[35] Wresearch. (n.d.). India Vinegar Market (2024-2030) | Trends, Outlook & Forecast. 6Wresearch. https://www.6wresearch.com/industry-report/india-vinegar-market

[36] Ahuja, K., & Kabra, H. (1970). Vinegar Market Size - By Product Type (White Vinegar, Apple Cider Vinegar, Balsamic Vinegar, Red Wine Vinegar, Rice Vinegar), Source (Organic, Synthetic), Flavor, Distribution Channel, Application, Growth Prospects, Regional Outlook & Forecast, 2023 – 2032. In Global Market InsightsInc.https://www.gminsights.com/industry-analysis/vinegar-market

[37] Vinegar(n.d.).https://cec.nic.in/webpath/curriculum/Module/FDTECH/Paper11/13/downloads/script.pdf

[38] Raghuwanshi, R. (n.d.). Vinegar Production. https://www.bhu.ac.in/Content/Syllabus/Syllabus_3006309920200412060036.pdf

[39] Ng, Y. (2018b, December 11). Vinegar production. SlideShare.https://www.slideshare.net/slideshow/vinegar-production/125557960

[40] Explain the preparation of acetic acid by a quick vinegar process with diagram. (n.d.). https://www.vedantu.com/question-answer/explain-the-preparation-of-acetic-acid-by-a-class-11-chemistry-cbse-5f83026fd998131f75fe1d4e

[41] N, S. (2021, February 12). Acetic Acid Production. Biology Reader. https://biologyreader.com/acetic-acid-production.html

[42] Gullo, M., Verzelloni, E., & Canonico, M. (2014). Aerobic submerged fermentation by acetic acid bacteria for vinegar production: Process and biotechnological aspects. Process Biochemistry, 49(10),1571–1579. https://doi.org/10.1016/j.procbio.2014.07.003

[43] LaBorde, L. (n.d.). Making Cider Vinegar at Home. https://extension.psu.edu/making-cider-vinegar-at-home#:~:text=To%20pasteurize%2C%20heat%20the%20vinegar,not%20exceed%20160%20degrees%20F

[44] Mendhe, S. N. (n.d.). INDUSTRIAL PRODUCTION OF VINEGAR (ACETIC ACID).SlideShare.https://shivajichk.ac.in/pdf/VINEGAR%20PRODUCTION%20%20PPT.pptx#:~:text=3)%20Clarification%3A%2D%20Clarification%20of,C%20for%20about%2030%20min

[45] Vinegar Production Process | Miyajima Shoyu. (2018b, April 23). 宮島醤油. https://www.miyajima-soy.co.jp/english-site/en-fermented-foods/about-vinegar

[46] Wang, Z. M., Lu, Z. M., Yu, Y. J., Li, G. Q., Shi, J. S., & Xu, Z. H. (2015). Batch-to-batch uniformity of bacterial community succession and flavor formation in the fermentation of Zhenjiang aromatic vinegar. Food Microbiology, 50, 64–69. https://doi.org/10.1016/j.fm.2015.03.012

[47] Hutchinson, U., Jolly, N., Chidi, B., Ngongang, M. M., & Ntwampe, S. (2019). Vinegar Engineering: A Bioprocess Perspective. Food Engineering Reviews, 11(4), 290–305.https://doi.org/10.1007/s12393-019-09196-x

[48] Ramanlal, R., & Gupta, V. (2023, January 23). Physiology, Vasodilation. StatPearls - NCBI Bookshelf.https://www.ncbi.nlm.nih.gov/books/NBK557562/

[49] Rudrapal, M., Khairnar, S. J., Khan, J., Dukhyil, A. B., Ansari, M. A., Alomary, M. N., Alshabrmi, F. M., Palai, S., Deb, P. K., & Devi, R. (2022). Dietary Polyphenols and Their Role in Oxidative Stress-Induced Human Diseases: Insights into Protective Effects, Antioxidant Potentials and Mechanism(s) of Action. Frontiers in Pharmacology, 13. https://doi.org/10.3389/fphar.2022.806470

[50] Grillo, N., Salvi, N., Coruzzi, N., Salvi, N., & Parati, N. (2019). Sodium Intake and Hypertension. Nutrients, 11(9), 1970. https://doi.org/10.3390/nu11091970

[51] Kondo, S., Tayama, K., Tsukamoto, Y., Ikeda, K., & Yamori, Y. (2001). Antihypertensive Effects of Acetic Acid and Vinegar on Spontaneously Hypertensive Rats. Bioscience, Biotechnology, and Biochemistry, 65(12), 2690–2694. https://doi.org/10.1271/bbb.65.2690

[52] Maruta, H., Yoshimura, Y., Araki, A., Kimoto, M., Takahashi, Y., & Yamashita, H. (2016). Activation of AMP-Activated Protein Kinase and Stimulation of Energy Metabolism by Acetic Acid in L6 Myotube Cells. PloS One, 11(6), e0158055. https://doi.org/10.1371/journal.pone.0158055

[53] Kalyan, A. R. (n.d.). Apple cider vinegar for weight loss. https://continentalhospitals.com/blog/apple-cider-vinegar-for-weight-loss

[54] Xia, T., Kang, C., Qiang, X., Zhang, X., Li, S., Liang, K., Wang, Y., Wang, J., Cao, H., & Wang, M. (2024b). Beneficial effect of vinegar consumption associated with regulating gut microbiome and metabolome. Current Research in Food Science, 8, 100566. https://doi.org/10.1016/j.crfs.2023.100566

[55] Ousaaid, D., Laaroussi, H., Bakour, M., ElGhouizi, A., Aboulghazi, A., Lyoussi, B., & ElArabi, I. (2020). Beneficial Effects of Apple Vinegar on Hyperglycemia and Hyperlipidemia in Hypercaloric-Fed Rats. Journal of Diabetes Research, 2020, 1–7. https://doi.org/10.1155/2020/9284987

[56] Ayua, E. O., Nkhata, S. G., Namaumbo, S. J., Kamau, E. H., Ngoma, T. N., & Aduol, K. O. (2021). Polyphenolic inhibition of enterocytic starch digestion enzymes and glucose transporters for managing type 2 diabetes may be reduced in food systems. Heliyon, 7(2), e06245. https://doi.org/10.1016/j.heliyon.2021.e06245

[57] Fushimi, T., Tayama, K., Fukaya, M., Tsukamoto, Y., Kitakoshi, K., Nakai, N., & Sato, Y. (2001b). Acetic Acid Feeding Enhances Glycogen Repletion in Liver and Skeletal Muscle of Rats. the Journal of Nutrition/ the Journal of Nutrition, 131(7), 1973–1977. https://doi.org/10.1093/jn/131.7.1973

[58] Petsiou, E. I., Mitrou, P. I., Raptis, S. A., & Dimitriadis, G. D. (2014). Effect and mechanisms of action of vinegar on glucose metabolism, lipid profile, and body weight. Nutrition Reviews, 72(10),651661.https://doi.org/10.1111/nure.12125

[59] Wu, Q., Kong, Y., Liang, Y., Niu, M., Feng, N., Zhang, C., Qi, Y., Guo, Z., Xiao, J., Zhou, M., He, Y., & Wang, C. (2023). Protective mechanism of fruit vinegar polyphenols against AGEs-induced Caco-2 cell damage. Food Chemistry. X, 19, 100736. https://doi.org/10.1016/j.fochx.2023.100736

[60] Bhattacharyya, A., Chattopadhyay, R., Mitra, S., & Crowe, S. E. (2014c). Oxidative Stress: An Essential Factor in the Pathogenesis of Gastrointestinal Mucosal Diseases. Physiological Reviews, 94(2), 329–354. https://doi.org/10.1152/physrev.00040.2012

[61] Chen, X., Li, H., Zhang, B., & Deng, Z. (2021). The synergistic and antagonistic antioxidant interactions of dietary phytochemical combinations. Critical Reviews in Food Science and Nutrition, 62(20), 5658–5677. https://doi.org/10.1080/10408398.2021.1888693

[62] Oeckinghaus, A., & Ghosh, S. (2009). The NF- B Family of Transcription Factors and Its Regulation. Cold Spring Harbor Perspectives in Biology, 1(4), a000034. https://doi.org/10.1101/cshperspect.a000034

[63] Balaji, S., & Ganesan, K. K. (2021). Inhibition of inducible nitric oxide production by Caryota urens and its active constituents umbelliferone and rutin. Journal of Ayurveda and Integrative Medicine, 12(2), 369–372. https://doi.org/10.1016/j.jaim.2020.09.002

[64] Yui, K., Imataka, G., Nakamura, H., Ohara, N., & Naito, Y. (2015). Eicosanoids Derived from Arachidonic Acid and Their Family Prostaglandins and Cyclooxygenase in Psychiatric Disorders. Current Neuropharmacology, 13(6), 776–785. https://doi.org/10.2174/1570159x13666151102103305

[65] Professional, C. C. M. (n.d.). Indigestion (Dyspepsia). Cleveland Clinic. https://my.clevelandclinic.org/health/symptoms/7316-indigestion-dyspepsia

[66] Dietary Acids and Your Teeth | MouthHealthy - Oral Health Information from the ADA. (n.d.). https://www.mouthhealthy.org/en/all-topics-a-z/dietary-acids-and-your-teeth#:~:text=Foods%20and%20beverages%20that%20are,can%20cause%20cavities%20or%20infection

[67] Huzar, T. (2023, April 3). Side effects of apple cider vinegar. https://www.medicalnewstoday.com/articles/324184#:~:text=reduces%20this%20risk.-,Low%20potassium,should%20seek%20medical%20attention%20immediately

[68] King, L. M. (2024, February 5). Indigestion (Dyspepsia): Symptoms, Causes, and Treatments. WebMD. https://www.webmd.com/heartburn-gerd/indigestion-overview#:~:text=However%2C%20indigestion%20is%20often%20caused,from%20too%20little%20stomach%20acid

[69] Team, Z. A. (2023, March 1). 13 Best Apple Cider Vinegar Benefits in Ayurveda, Uses & Consumption. Zanducare. https://zanducare.com/blogs/exploring-ayurveda/apple-cider-vinegar-benefits-uses-ayurvedic-products

[70] Jo. (2023, June 28). Making vinegar from fruit scraps.Replenish.https://replenishoxfordshire.com/2023/06/28/making-vinegar-from-fruit-scraps/#:~:text=Citrus%20fruits%2C%20like%20lemons%20and,to%20use%20them%20for%20vinegar

[71] Saha, D., & Das, P. K. (2023). Bioconversion of Agricultural and Food Wastes to Vinegar. In IntechOpeneBooks.https://doi.org/10.5772/intechopen.109546

[72] Chen, Z. (2023). Food Safety and Quality: Importance, Challenges, and Solutions. Longdom. https://doi.org/10.35248/2476-2059.23.8.211

[73] Luzón-Quintana, L. M., & Castro, R. (2021b). Biotechnological Processes in Fruit Vinegar Production. Foods, 10(5), 945. https://doi.org/10.3390/foods10050945