Fruit Seed Waste as a Resource for Anti-Inflammatory Therapeutics: A Circular Economy Perspective

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Abstract

Seeds, an integral yet often discarded component of fruits, represent a substantial source of bioactive compounds and an underutilized resource in agro-food waste streams. The valorization of fruit seed waste from orange, papaya, dates, java plum, avocado, cherry, and mango offers a sustainable approach aligned with the principles of circular economy, waste management, and resource recovery. Historically, Indian Ayurvedic practices have utilized various fruit seeds in medicinal formulations, highlighting their long-standing therapeutic relevance. Fruit seeds, commonly treated as waste, possess significant anti-inflammatory potential due to their rich phytochemical composition, including flavonoids, carotenoids, tocopherols, phytosterols, and triterpenoids. These bioactive compounds modulate key inflammatory signalling pathways such as Mitogen-Activated Protein Kinase (MAPK) and Nuclear Factor Kappa B (NF-êB). This review emphasizes the role of fruit seed-derived bioactive molecules in suppressing pro-inflammatory mediators including histamine, serotonin, tumour necrosis factor-alpha (TNF-á), interleukins (IL-6, IL-1), nitric oxide (NO), and reactive oxygen species (ROS). The sustainable recovery and utilization of these compounds from fruit processing waste presents promising strategies for managing acute inflammation and inflammation-associated disorders such as cancer,

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cardiovascular diseases, diabetes, rheumatoid arthritis, allergic asthma, chronic obstructive pulmonary disease (COPD), lupus, Crohn's disease, neurodegenerative disorders, atherosclerosis, and anxiety. This review highlights the transformative potential of converting fruit seed waste into high-value anti-inflammatory therapeutics, contributing to waste minimization, resource efficiency, and sustainable drug development.

Keywords: *Agro-food waste; Ayurvedic practices; Flavonoids; MAPK; Neurodegenerative disorders*

1. Introduction

The rapid growth of the food, cosmetics, and pharmaceutical industries has resulted in large-scale generation of agro-industrial waste, particularly fruit seeds, which are often discarded despite their rich biochemical potential. In countries such as India, inadequate management of fruit processing by-products contributes to environmental pollution and loss of valuable resources. Emerging evidence indicates that fruit seeds are abundant in phenolic compounds and other bioactive constituents with significant therapeutic effects. Their valorization through sustainable extraction strategies supports circular economy principles and resource recovery. Converting fruit seed waste into affordable natural anti-inflammatory agents offers a dual benefit—reducing environmental burden while addressing inflammation-related disorders. Thus, fruit seed utilization represents a practical link between sustainability and human health.

Phytochemicals are naturally occurring plant compounds with diverse structures and biological functions. They contribute to plant defense and reproduction through mechanisms such as toxin production, pathogen resistance, and pollinator attraction [1]. When consumed, these compounds exhibit bioactive effects in humans, providing multiple health benefits supported by extensive in vitro and in vivo studies over the past two decades [2]. Phytochemicals are widely distributed in fruits, vegetables, whole grains, legumes, seeds, and nuts, and are associated with protection against diseases such as cancer, diabetes, cardiovascular disorders, asthma, arthritis, and infections. Seeds, as integral components of fruits, contain concentrated bioactive compounds, as summarized in **[Table 1]**. Seeds of orange, papaya, date, Java plum, avocado, cherry, and mango demonstrate promising anti-inflammatory potential and have been traditionally used in Ayurvedic medicine for therapeutic preparations. Despite this historical relevance, these seeds are now commonly discarded after consumption, overlooking their medicinal and economic value. Repurposing fruit seeds can reduce waste, enhance natural medicine applications, and support sustainable bioeconomy development [3]. Inflammation, whether acute or chronic, is associated with numerous disorders, including cancer, cardiovascular disease, diabetes, rheumatoid arthritis, asthma, chronic obstructive pulmonary disease (COPD), lupus, Crohn's disease, neurodegenerative conditions, and atherosclerosis. While redness, swelling, and pain are typical protective immune responses, excessive or prolonged inflammation can become harmful when immune regulation fails.

1.1. Types of phytochemicals in seeds

Bioactive compounds in seeds, such as flavonoids, phenolic compounds, phytosterols, carotenoids, triterpenoids, and tocopherol, have shown promising potential as natural treatments for inflammatory diseases. These phytochemicals can modulate inflammatory pathways through specific molecular mechanisms, such as increasing anti-inflammatory cytokine production or inhibiting pro-inflammatory cytokines [4]. Inflammatory cytokines are signalling molecules produced by immune cells (or other cell types) to stimulate the inflammatory response. By leveraging the anti-inflammatory properties of seed-derived bioactive compounds, we may have an effective, natural means to combat inflammation and reduce disease impact [5].

Table 1. Types of phytochemicals present in Seeds

S.No.	Name of Phytochemicals	Types
1	Phenolic compounds	Catechin, hydroxybenzoic acid, chlorogenic acid, coumaric acid, salicin, ferulic acid, etc
2	Tocopherols	Alpha-tocopherol, beta-tocopherol, gamma-tocopherol, and delta-tocopherol.
3	Phytosterols	Campesterol, beta-sitosterol, stigmasterol, etc
4	Flavonoids	Curcumin, luteolin, isoflavone, rosmarinic acid, isoorientin, glabridin, quercetin, liquirtin etc.
5	Carotenoids	Alpha-carotene, beta-carotene, lutein, beta-cryptoxanthin, fucoxanthin, etc.
6	Triterpenoids	Ursane, oleanane, lupane, dammarane, euphane, etc.

1.2. Structures of phytochemicals

Structures of phytochemicals such as phenolic compounds, flavonoids and terpenes are depicted in **[Figures 1, 2, and 3]**, respectively.

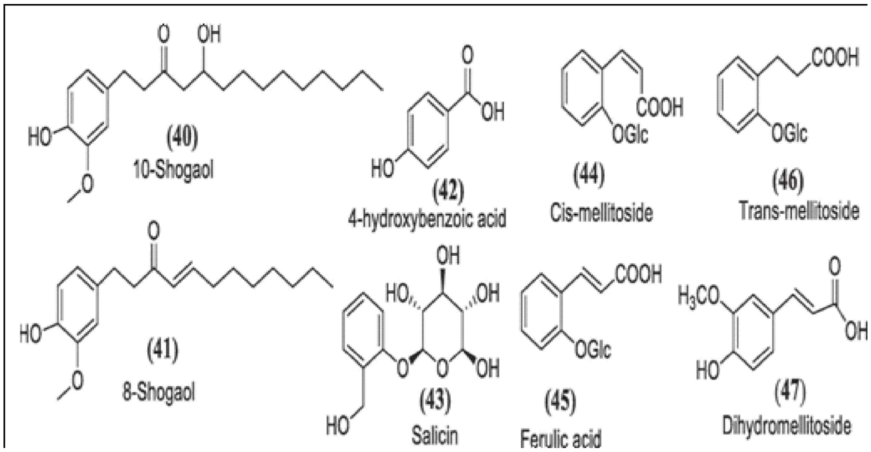

Figure 1. Chemical structures of some phenolic compounds with anti-inflammatory activity[4].

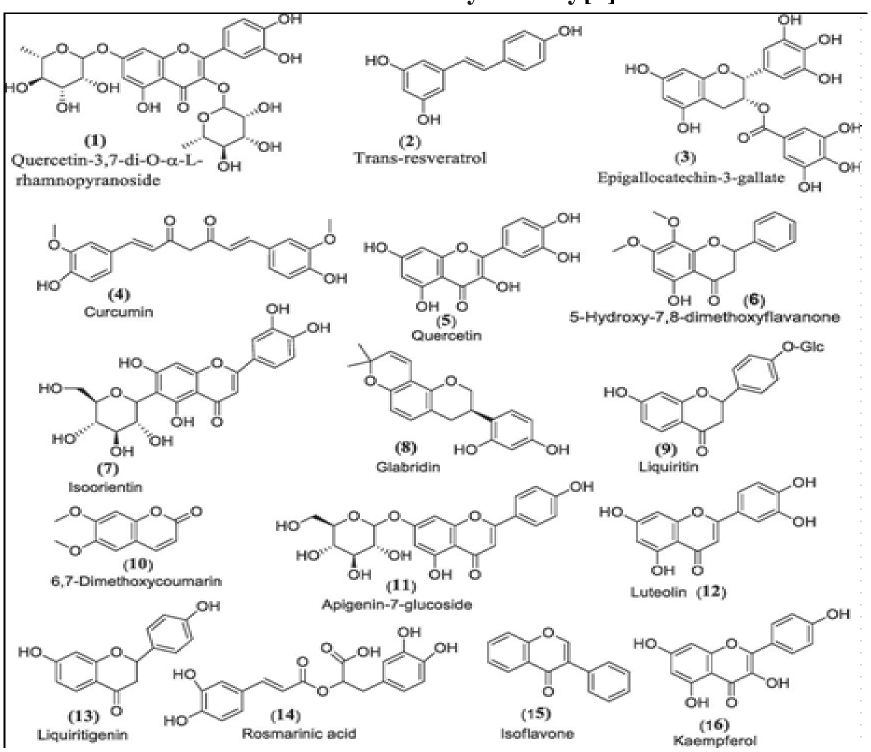

Figure 2. Chemical structures of some flavonoids with anti-inflammatory activity [4].

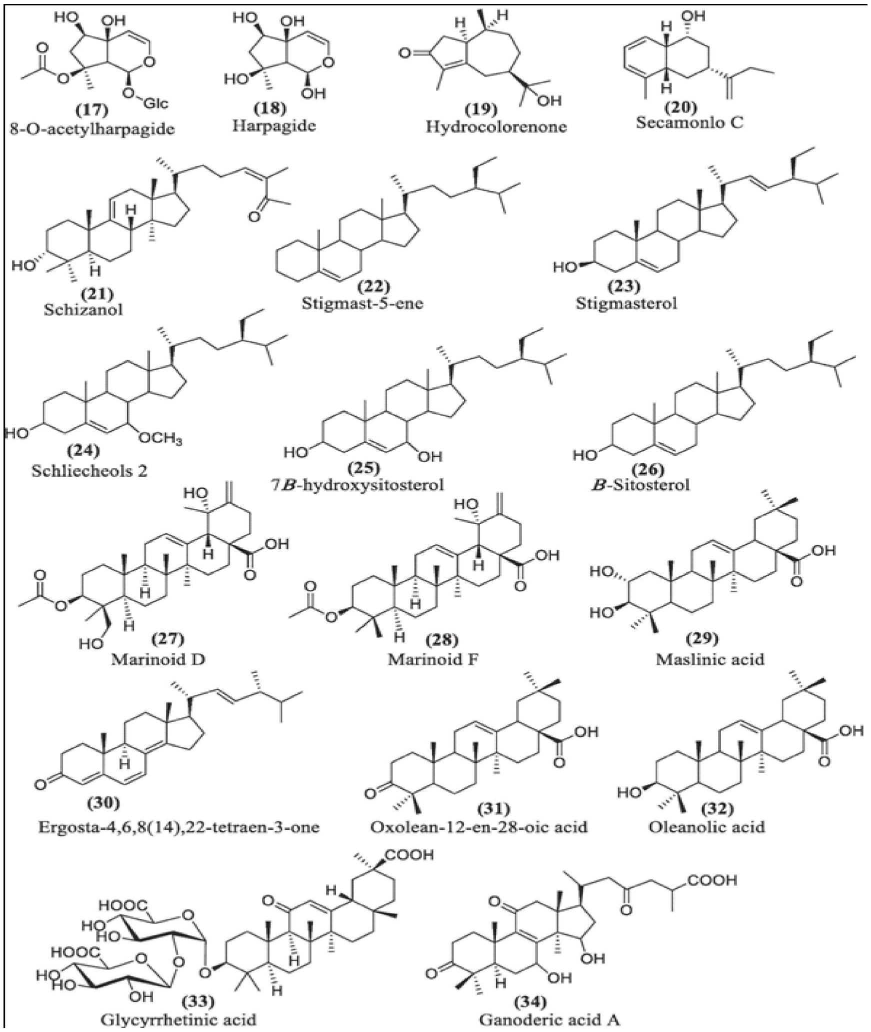

Figure 3. Chemical structures of some terpenes with anti-inflammatory activity [4].

2. Inflammation

Inflammation is a protective biological response triggered by infections (viruses, bacteria), toxic agents, or tissue injury. It is classified into acute and chronic forms [**Figure 4**]. Acute inflammation is characterized by pain, redness, heat, swelling, and loss of function; when unresolved, it may progress to chronic inflammation [**Figure 5].** The immune system regulates this process throughout. Inflammation involves the release of mediators such as histamine, serotonin, tumour necrosis factor-alpha (TNF-á), interleukin-6 (IL-6), IL-1, nitric oxide (NO), and reactive oxygen species (ROS). These mediators activate receptors including toll-like receptors (TLRs), pathogen-associated molecular patterns (PAMPs), damage-associated molecular patterns (DAMPs), and pattern recognition receptors (PRRs), along with immune cells [**Figure 6**]. Receptor activation initiates signalling pathways such as mitogen-activated protein kinase (MAPK) and nuclear factor kappa-B (NF-êB), leading to transcription of pro-inflammatory genes and recruitment of immune cells to the affected site. In chronic inflammation, elevated ROS—primarily produced by neutrophils—further regulate kinases and transcription factors that sustain pro-inflammatory gene expression. Overall, inflammation is a highly complex and tightly regulated biological process [6].

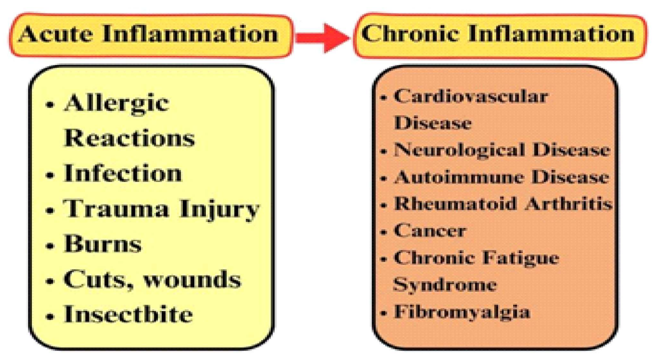

Figure 4. Types of Inflammation

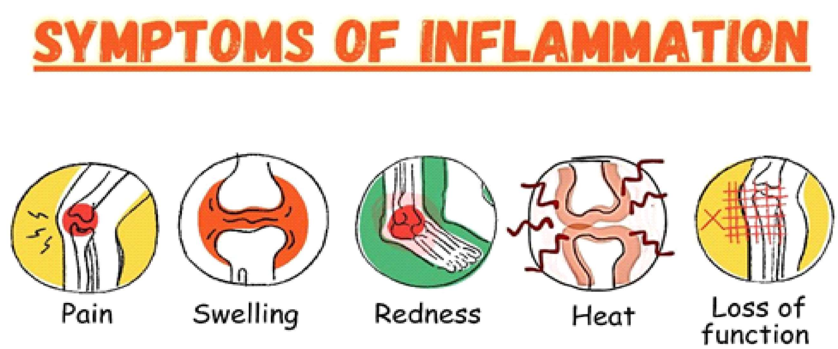

Figure 5. Common Symptoms of Inflammation

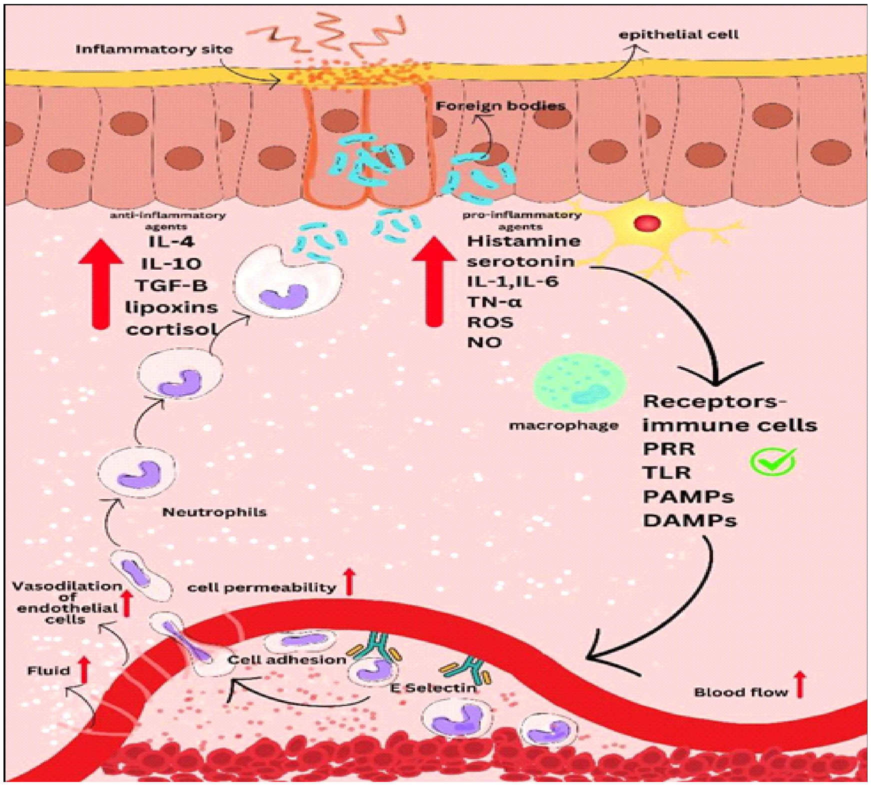

Figure 6. Mechanism of Inflammation

3. Flavonoids

Flavonoids are hydroxylated polyphenolic compounds characterized by two aromatic rings linked through a heterocyclic pyran ring (C6–C3–C6 backbone) and typically occur in glycosylated or aglycone forms. They are widely distributed secondary metabolites in plants, including fruit seeds, and perform diverse biological functions. At the cellular level, flavonoids exhibit anti-inflammatory activity by inhibiting pro-inflammatory mediators such as eicosanoids, cytokines, adhesion molecules, and C-reactive protein (CRP). They also suppress transcription factors including NF-êB and activator protein-1 (AP-1), while promoting activation of nuclear factor erythroid 2–related factor 2 (Nrf2).

Dietary habits significantly influence the development of degenerative diseases. Persistent inflammation can induce inflammatory stress, contributing to endothelial dysfunction and risk factors associated with cardiovascular and other chronic disorders, including obesity, hyperglycemia, and dyslipidaemia. More than 8000 polyphenols have been identified, many sharing hydroxylated aromatic structures and representing major components of the human diet. Flavonoids are classified into subclasses such as flavanones, flavones, flavonols, and isoflavones, as illustrated in [**Figure 7],** with additional structural representations shown in [**Figure 2**]. Catechins are among the most abundant flavonoids. Epidemiological evidence indicates that higher flavonoid intake is associated with reduced risk of cardiovascular disease and cancer [6].

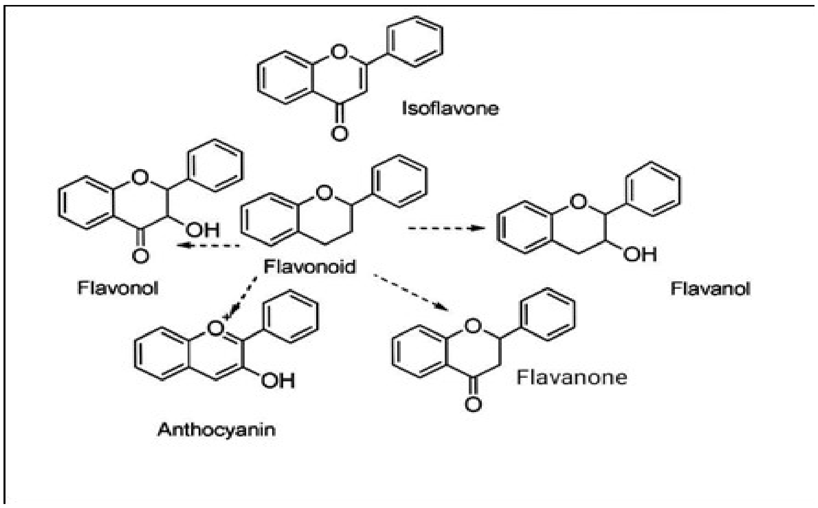

Figure 7. Chemical Structure of flavonoids and their different types [8]

Flavonoids are widely distributed in vegetables, fruits, herbs, seeds, and flowers. This review primarily focuses on seeds due to their significant medicinal potential. Flavonoids exert anti-inflammatory effects by activating antioxidant pathways and inhibiting the release of inflammatory enzymes such as lysozyme and â-glucuronidase, as well as suppressing arachidonic acid metabolism, thereby reducing inflammatory responses [7]. In addition to anti-inflammatory activity, flavonoids exhibit antioxidant, analgesic, antimicrobial, antiviral, anti-malarial, antiproliferative, anticancer, antigenic, and neuroprotective properties [8]. The immune system recognizes pathogens and harmful substances through specific cell surface receptors. Upon activation, pro-inflammatory pathways are triggered, leading to increased production of cytokines and activation of immune cells such as macrophages and lymphocytes. Failure to eliminate these agents at the initial stage can result in persistent inflammation, characterized by excessive production of cytokines, chemokines, and inflammatory enzymes. Cytokine production is regulated at the transcriptional level and may either amplify or suppress inflammation. Key mediators include TNF, IL-1â, IL-6, IL-8, and monocyte chemoattractant protein-1, studied in various cell types such as RAW macrophages, Jurkat T-cells, and peripheral blood mononuclear cells [9]. Major inflammatory signalling pathways include receptor-mediated mechanisms, toll-like receptors, mitogen-activated protein kinase (MAPK), and nuclear factor kappa-B (NF-êB), which regulates numerous inflammation-related genes [**Figure 8**] [10]. Cyclooxygenase-2 (COX-2), regulated by NF-êB and cytokines, promotes prostaglandin E2 (PGE2) synthesis and recruits neutrophils, leading to release of cytokines, reactive oxygen species (ROS), and histamine, thereby inducing pain and inflammation (Figure 8). Dysregulation of these pathways contributes to inflammatory disorders [11].

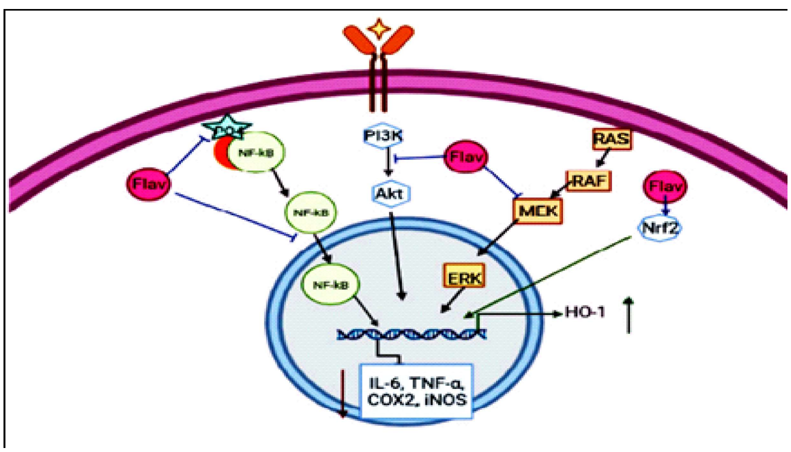

Figure 8. Inflammatory pathways targeted by flavonoids [8]

3.1. Mechanism of flavonoids as an anti-inflammatory agent

In vitro studies demonstrate that flavonoids exert anti-inflammatory effects by modulating key molecular targets, including cyclooxygenase-2 (COX-2), lipoxygenase (LOX), inducible nitric oxide synthase (iNOS), nuclear factor kappa-B (NF-êB), activator protein-1 (AP-1), mitogen-activated protein kinase (MAPK), protein kinase C, and phase II antioxidant enzymes. Quercetin and kaempferol inhibit COX-2 activity in rat peritoneal macrophages [12]. Kaempferol, quercetin, morin, and myricetin suppress lipoxygenase, whereas naringenin shows minimal effect. In lipopolysaccharide (LPS)-stimulated macrophages, apigenin and luteolin reduce nitric oxide (NO) production, while catechin and flavanones are ineffective below 100 µM [13].

As exogenous antioxidants, flavonoids scavenge reactive species by inhibiting nitric oxide synthase and xanthine oxidase and by modulating ion channels. They also reduce low-density lipoprotein (LDL) oxidation by limiting peroxynitrite formation generated from NO and superoxide in activated macrophages [8]. Flavonoids are absorbed in the stomach and small intestine via passive diffusion or active transport, and specific hydroxyl substitutions enhance their antibacterial and anti-inflammatory activities.

Catechin and quercetin promote the production of the anti-inflammatory cytokine IL-10 while suppressing IL-1 and TNF-á expression [8]. Quercetin inhibits heat shock factor activation, reducing heat shock protein (HSP70) induction and cellular stress responses [14]. It also suppresses NO synthase and TNF-á expression in LPS-induced RAW cells through inhibition of MAPK signalling and AP-1 DNA binding [14]. Apigenin downregulates mRNA expression of intercellular adhesion molecule-1 (ICAM-1), E-selectin, and vascular cell adhesion molecule-1 (VCAM-1) in endothelial cells and reduces TNF-á, IL-1, IL-6, and prostaglandin production. Genistein similarly inhibits IL-1, IL-6, and TNF-á in LPS-treated RAW cells. Flavonoids further reduce arachidonic acid metabolites and chemokines, thereby limiting leukocyte infiltration and oedema. Their ability to chelate iron and inhibit complement activation decreases reactive oxygen species (ROS) generation and attenuates inflammatory responses[15].

4. Carotenoids

Carotenoids (CTs) are tetraterpenoids composed of eight C5 isoprenoid units forming conjugated polyene chains. The trans isomer predominates in nature, while cis isomers have lower melting points due to reduced crystallization. Carotenoids are lipophilic, insoluble in water, but soluble in organic solvents such as ethanol, acetone, ethyl acetate, ether, and chloroform. Their hydrophobic structure enables penetration of the blood–brain barrier. Cis isomers absorb light at shorter wavelengths [16].

Carotenoids are synthesized not only in photosynthetic tissues but also in non-photosynthetic plant organs including flowers, roots, seeds, pericarp, and fruits through secondary metabolic reactions such as cis/trans (Z/E) isomerisation, oxidative cleavage, and polyene modification. In plants, they function as hormone precursors, antioxidants, photoprotective agents, and colour pigments responsible for fruit ripening. In photosynthetic organisms such as algae and bacteria, carotenoids contribute to photoprotection and photosynthesis alongside chlorophylls [17].

Carotenoids are classified into two groups: hydrocarbon carotenes and oxygenated xanthophylls. Carotenes are non-polar compounds, including phytoene, phytofluene, lycopene, and â-carotene **[Figure 9].** Xanthophylls are polar due to oxygen-containing functional groups such as hydroxyl, keto, epoxy, or carboxy groups; examples include lutein and fucoxanthin [**Figure 10**]. Many carotenes serve as vitamin A precursors in humans. Carotenoids also exhibit anti-inflammatory effects, particularly in neurodegenerative conditions, and diets rich in carotenoids are associated with reduced inflammation-related diseases [Table 2] [17].

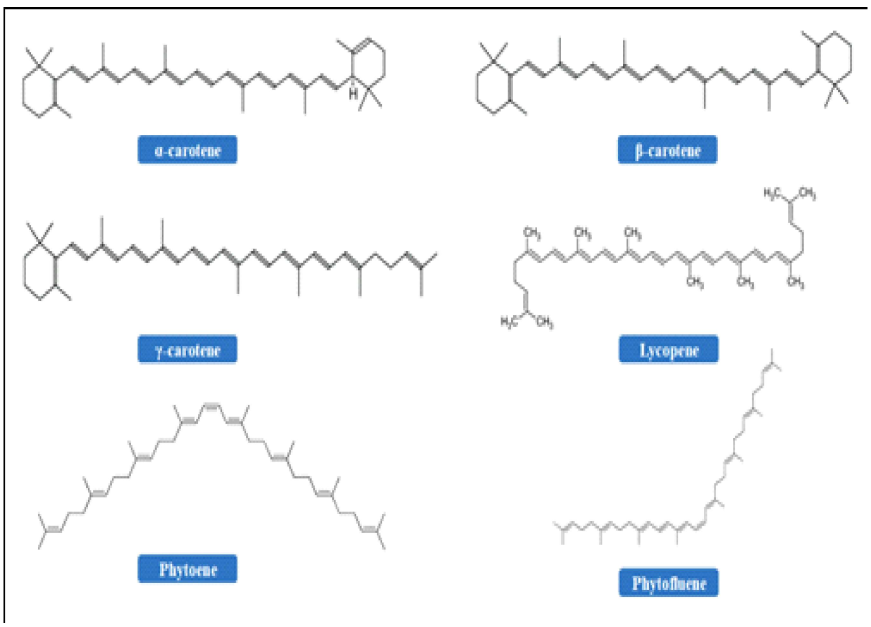

Figure 9. Structure of Hydrocarbon Carotenoids [17]

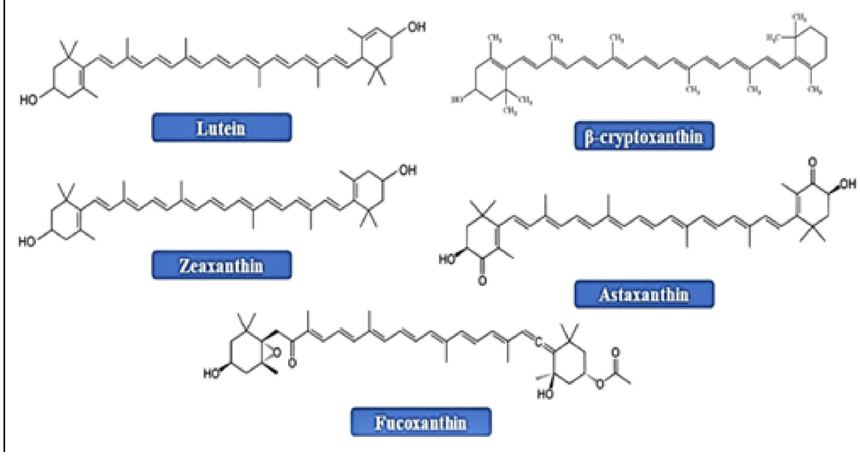

Figure 10. Structures of xanthophylls [17]

Table 2. Anti-inflammatory effects of various food-derived carotenoids and the viruses in neurodegenerative disorder (ND)[17]

S.No.	Carotenoids	Property	Implication in ND
1	Astaxanthin	neuroinflammatory	Alzheimer Disease
2	Crocetin	neuroinflammatory	Alzheimer Disease
3	Lycopene	neuroinflammatory	Alzheimer Disease
4	Crocin	neuroinflammatory	Alzheimer Disease
5	Fucoxanthin	neuroinflammatory	Alzheimer Disease
6	Lutein	neuroinflammatory	Alzheimer's Disease and Parkinson's Disease

4.1. Mechanism of carotenoids as an anti-inflammatory agent

Neuro-inflammation is an inflammatory reaction of the nervous system during autoimmune disorders and trauma. Neurodegeneration cells are linked with neuro-inflammation. CTs showed anti-neuroinflammatory properties in vivo. Lutein decreases the production of proinflammatory cytokines and lipid peroxidation by inhibiting the activation of the nuclear factor-kB (NF-êB) signalling pathway [17].

Crocetin and crocin decrease the generation of NO (nitric oxide) and pro-inflammatory cytokines via interferon-gamma, lipopolysaccharide, and A β induction in microglia[18].

NF-êB controls the expression of various jeans such as (inflammation-associated and OS-responsive genes). This results in an increased level of ROS in the brains of individuals with NDs might result in an inflammatory reaction. CTs can decrease ROS levels to alleviate cellular injury and simultaneously decrease the rate of inflammatory reaction by decreasing the function of NF-êB. Multiple studies confirmed that several CTs bit inflammation by suppressing the function of NF-êB [17].

Lycopene reduced mitochondrial OS and suppressed NF-êB function and pro-inflammatory cytokines in the brains of AD mouse models [19]. The results were improved memory retention and inhibition of Abeta generation [16]. CTS are natural products that contain a high therapeutic activity against NDs **[Figure 11]**.

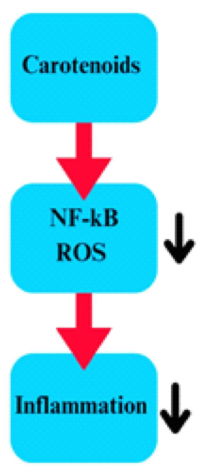

Figure 11. Carotenoids as anti-inflammatory agents

5. Tocopherol

Alpha-tocopherol and gamma-tocopherol contain anti-inflammatory properties. Alpha and beta are two major forms of vitamin E in human tocopherol and tocotrienol both possess a common chromanol ring that is methylated to different degrees at the 5 prime and 7 prime positions giving yield to the four different forms alpha, beta, gamma, and delta **[Figure 12]**. Tocopherols have a saturated phytyl side chain, naturally occurring tocopherols contain three centres with a configuration of R at position 2‘, 4‘ and 8‘ hence natural tocopherols are RRR [20].

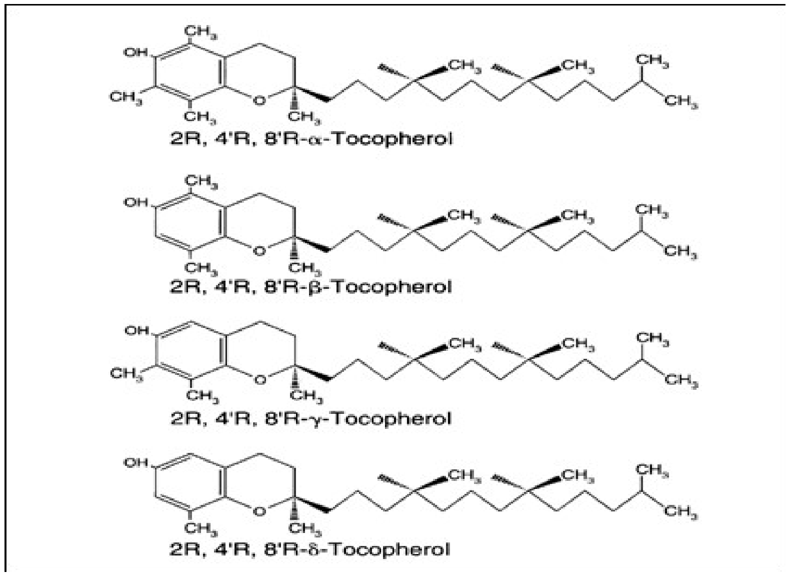

Figure 12. Structure of different types of tocopherols [21]

5.1. Anti-inflammatory properties of tocopherol

Ageing increases oxidative stress and weakens immune function, predisposing individuals to infections, autoimmune disorders, and chronic inflammatory diseases such as atherosclerosis, cancer, and neurodegenerative conditions including Alzheimer's disease [20]. Vitamin E (á-tocopherol) has been shown to enhance immune response quality and has gained attention for its potential role in cardiovascular disease (CVD) prevention. Atherosclerosis, a major contributor to CVD, involves oxidation of low-density lipoprotein (LDL), a process inhibited by á-tocopherol in numerous in vitro studies [20].Patients with diabetes are at increased risk of developing CVD. Vitamin E supplementation exhibits anti-inflammatory effects on isolated monocytes and reduces in vivo inflammatory markers. It lowers superoxide, hydrogen peroxide, lipid peroxides, IL-1 levels, and plasma C-reactive protein (CRP) in individuals with type 2 diabetes. Reduced CRP levels are associated with decreased LPS-induced IL-6 production in isolated monocytes [22].

The molecular targets of á- and ã-tocopherol and their modulation of inflammatory signalling pathways are illustrated in **Figure 13**. These include regulation of protein kinase C (PKC), which influences IL-1 production, COX-2 expression, and NADPH oxidase–mediated superoxide ($O_2\bullet^-$) generation, thereby contributing to their anti-inflammatory effects.

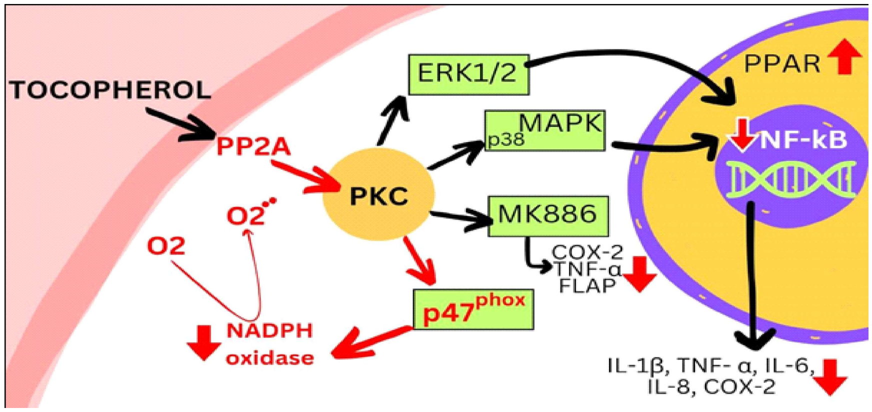

Figure 13. Possible molecular mechanisms of the anti-inflammatory effects mediated by tocopherol

α-Tocopherol inhibits phorbol 12-myristate (PMA)-induced superoxide ($O_2\bullet^-$) production in monocytes by suppressing protein kinase C (PKC) activity through protein phosphatase 2A (PP2A). It also reduces ERK1/2 and p38 MAPK phosphorylation, leading to decreased NF-κB DNA-binding activity. Inhibition of ERK1/2 signalling contributes to reduced COX-2 upregulation and prostaglandin E2 (PGE2) synthesis. MK886 suppresses COX-2, TNF-*α*, and 5-lipoxygenase activating protein (FLAP), thereby inhibiting leukotriene biosynthesis, a key inflammatory pathway. Peroxisome proliferator-activated receptors (PPARs), a family of transcription factors, exert anti-inflammatory effects by increasing PPAR transcriptional activity and inhibiting NF-κB–dependent gene expression, which reduces inflammatory cytokine production. γ-Tocopherol is reported to be more effective than *α*-tocopherol in inhibiting cyclooxygenase and lipoxygenase activity in vivo. Overall, both *α*- and *α*-tocopherol demonstrate promising anti-inflammatory potential in chronic inflammatory conditions [20].

6. Phytosterols

Phytosterols are known as plant sterols. Mainly these are sterols and stanols. The structure of plant sterols is similar to cholesterol but the side chain contains a methyl (campesterol) or ethyl *β*-sitosterol and sigma sterol group **[Figure 14]**. Sitostanol, campestanol, and stigmastanol are saturated forms of plant steroids hence called stanols [23].

6.1. Anti-inflammatory effect of phytosterols

β-sitosterol and campesterol are the most abundant sterols in human foods. This can reduce blood total cholesterol and low-density lipoprotein cholesterol (LDL-C) levels without affecting high-density lipoprotein cholesterol (HDL-C) levels. Plant sterol present in seeds has been shown to have anti-inflammatory properties in both humans and experimental animals [24].

Phytosterol contributed to improving lipid profiles and decreasing atherosclerosis lesions which are associated with inflammation. Phytosterols reduce the level of pro-inflammatory cytokines IL 6 and TN Alpha and increase the level of anti-inflammatory IL-10 in spleen cells from lipopolysaccharide (LPS) stimulated apolipoprotein E knockout mice (apo E-KO mice) fed with phytosterols [25].Phytosterols like -amyrin, and dimethyl sterol do not show cholesterol-lowering effects but have shown anti-inflammatory properties. Clinical studies have been able to determine the anti-inflammatory effect of phytosterols [24].

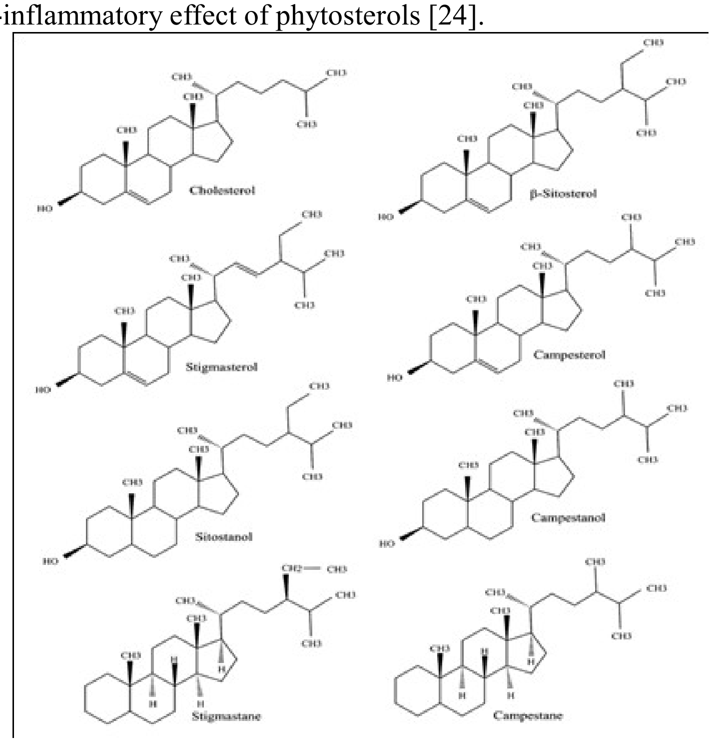

Figure 14. Structures of phytosterols [24]

7. Fruit Seed used to Treat Inflammation

Fruit seeds are rich in diverse phytoconstituents, including phenolic acids, flavonoids, carotenoids, tocopherols, phytosterols, and triterpenoids. The concentration and composition of these compounds vary among species, leading to differences in therapeutic efficacy. Seeds of orange, papaya, date, Java plum, avocado, cherry, and mango contain distinct bioactive profiles that contribute to their reported anti-inflammatory activities, as discussed above. The specific phytochemicals identified in each seed type are illustrated in the respective figures.

Orange seed phytochemicals [**Figure 15**] include caffeic acid, hesperidin, p-hydroxybenzoic acid, narirutin, and apigenin [28]. Papaya seeds **[Figure 16]** contain p-coumaric acid, kaempferol-3-glucoside, quercetin-3-galactoside, caffeic acid, ferulic acid, campesterol, stigmasterol, and â-sitosterol [29]. Java plum seeds **[Figure 17]** comprise epicatechin, apigenin, ferulic acid, â-sitosterol, p-coumaric acid, catechin, quercetin, rutin, ellagic acid, and gallic acid [26]. Date seeds **[Figure 18]** contain epicatechin, apigenin, catechin, quercetin, rutin, â-sitosterol, â-carotenoid, á- and â-tocopherol, and naringenin [27]. Avocado seeds **[Figure 19]** include caffeic acid, kaempferol, procyanidins, epicatechin, ferulic acid, rutin, catechin, and vanillic acid [30]. Cherry seeds **[Figure 20]** contain p-coumaric acid, catechin, quercetin, kaempferol, epicatechin, ferulic acid, naringenin-7-O-glucoside, and ellagic acid [31]. Mango seeds **[Figure 21]** comprise cinnamic acid, ferulic acid, quercetin, catechin, hesperidin, caffeic acid, mangiferin, gallic acid, and ellagic acid [32].

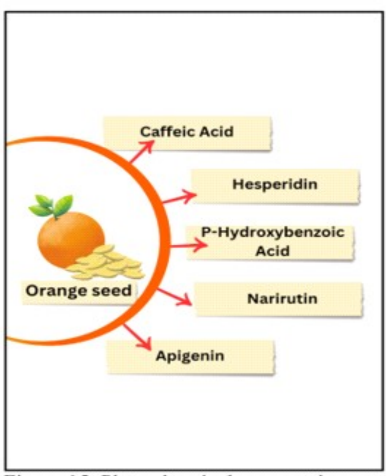

Figure 15. Phytochemicals present in orange seed.

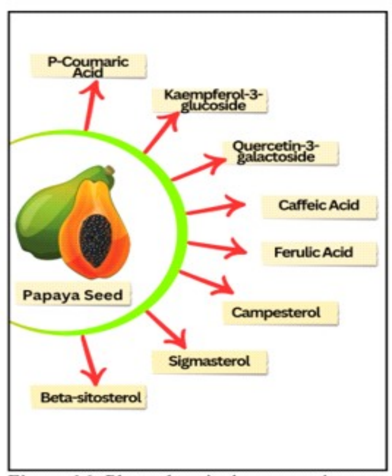

Figure 16. Phytochemicals present in papaya seed.

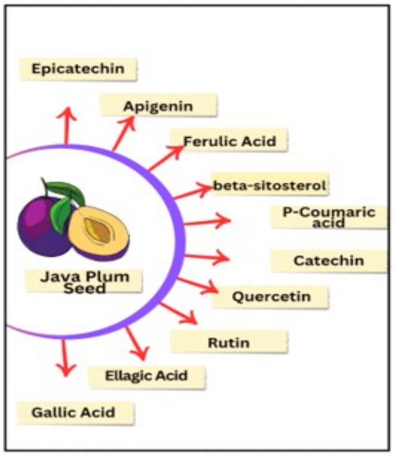

Figure 17. Phytochemicals present in java plum seed.

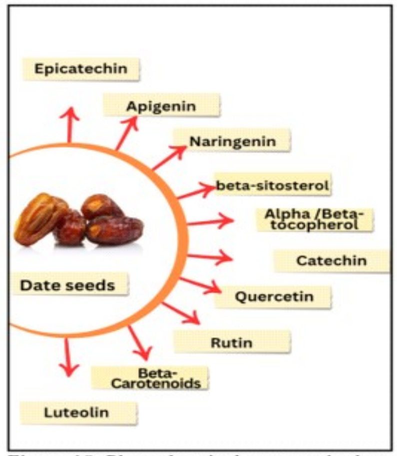

Figure 18. Phytochemicals present in date seed.

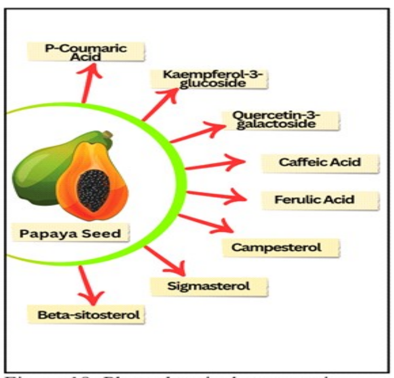

Figure 19. Phytochemicals present in avacado seed.

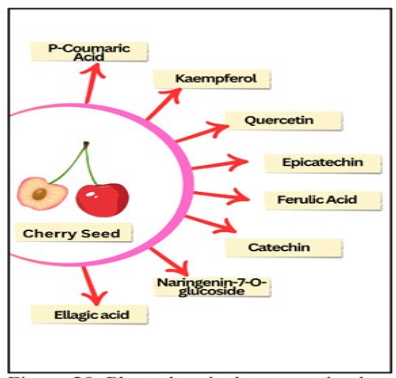

Figure 20. Phytochemicals present in cherry seed.

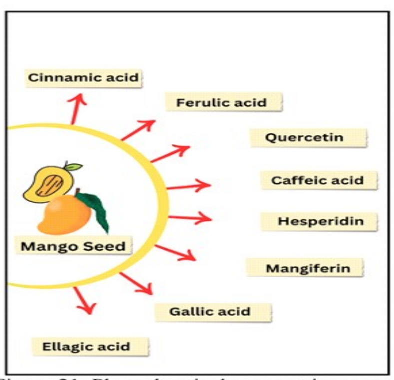

Figure 21. Phytochemicals present in mango seed.

8. Circular Economy Potential of Fruit Seed Waste

Fruit seeds are often discarded as industrial and household waste despite being rich sources of bioactive compounds. Their disposal contributes to environmental pollution and the loss of valuable natural resources. Seeds of mango, papaya, orange, avocado, cherry, and java plum contain abundant phenolics, flavonoids, and other antioxidants with notable anti-inflammatory activity. Recovering these compounds supports circular economy principles by converting waste into functional bioresources, reducing reliance on synthetic drugs and lowering production costs. Thus, fruit seed valorization promotes both environmental sustainability and affordable healthcare solutions [33]. With increasing global fruit production, sustainable technologies are urgently needed to convert fruit by-products into value-added materials, and efficient utilization of fruit side streams is essential for large-scale production of high-value ingredients. This chapter summarizes the chemical composition and biological activities of commonly consumed fruit seeds worldwide [34]. Conventional extraction of polyphenols relies on organic solvents such as methanol, ethanol, and acetone; however, these methods involve high solvent consumption and environmental concerns. Advanced approaches such as enzyme-assisted extraction improve phenolic release by degrading plant cell walls, with cellulases, pectinases, and hemicellulases commonly used to enhance extraction efficiency [35]. Ultrasound-assisted extraction utilizes acoustic cavitation to disrupt cellular matrices, thereby improving solvent penetration and compound recovery, particularly in seeds like avocado and grape [36]. Microwave-assisted extraction accelerates the process by rapidly heating polar solvents, achieving comparable or higher yields within significantly reduced timeframes. Pressurized hot water extraction modifies the polarity of water under high temperature and pressure, enabling selective extraction of phenolic compounds without organic solvents [34]. Additionally, supercritical fluid extraction, commonly employing carbon dioxide with ethanol as a modifier, is particularly suitable for thermolabile bioactives and has been successfully applied to grape and guava seeds. Optimization of these techniques is critical for maximizing polyphenol recovery while maintaining environmental sustainability within a circular economy framework [37].

Seeds of avocado (*Persea americana*) have emerged as a promising source of bioactive constituents with strong antioxidant and anti-inflammatory potential. Various solvent systems, including hydroalcoholic ethanol, aqueous methanol, aqueous acetone, and methanol–chloroform mixtures, have been used to obtain phytochemical-rich extracts. These extracts contain diverse fatty acids such as palmitic, linoleic, oleic, and stearic acids, along with phenolic acids including caffeic, ferulic, vanillic, p-coumaric, sinapic, and quinic acids. Flavonoids such as quercetin derivatives, naringenin, epicatechin, and procyanidin oligomers have also been identified. Reports consistently indicate high total phenolic content, correlating with strong antioxidant performance in DPPH and ABTS radical scavenging assays. Moreover, experimental studies demonstrate gastroprotective and anti-inflammatory effects, highlighting the potential of avocado seed waste as a valuable resource for nutraceutical and therapeutic development [35]. Overall, fruit seeds constitute a significant yet underutilized source of phytochemicals suitable for recovery within sustainable production systems. Bioactive-rich extracts show promising applications in both food and pharmaceutical sectors. Future research should prioritize the refinement of green extraction technologies and comprehensive evaluation of biological activities through in vitro and in vivo models. Following confirmation of safety and low toxicity profiles, these extracts may be further developed for incorporation into functional foods, cosmetics, and other health-promoting formulations [34].

9. Conclusion

The exploration of fruit seeds as anti-inflammatory agents establishes them as valuable bioresources rather than agro-industrial waste. Rich in flavonoids, carotenoids, tocopherols, and phytosterols, fruit seeds contain structurally diverse compounds that effectively modulate key inflammatory mediators, including TNF-á, IL-1, IL-6, NO, and ROS. Evidence from orange, papaya, date, Java plum, avocado, cherry, and mango seeds confirms their therapeutic potential against inflammation-related disorders such as cardiovascular diseases, diabetes, cancer, and autoimmune conditions. By linking waste valorisation with therapeutic application, this review reinforces the role of fruit seeds within a circular economy framework. Their utilization not only reduces environmental burden but also supports the development of sustainable, cost-effective anti-inflammatory interventions. Future research should prioritize bioavailability, clinical validation, and scalable formulations to enable successful integration of fruit seed-derived bioactives into pharmaceutical and nutraceutical systems.

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