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GREEN CHEMISTRY AND SUSTAINABLE TECHNOLOGIES

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Mr. Sanjay Gaikwad
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Preface

In the face of escalating environmental challenges and growing concerns about resource depletion, the need for a transformative approach to chemistry and technology has become more urgent than ever. Green Chemistry and Sustainable Technologies emerges from this pressing global necessity—to develop and implement scientific innovations that are not only effective but also environmentally benign, economically viable, and socially responsible.

This book brings together a wide spectrum of research, perspectives, and case studies that reflect the evolving landscape of green chemistry and sustainable technological advancements. It is designed to serve as a platform for academicians, researchers, industry professionals, and policy makers to explore and understand the pivotal role of sustainable science in shaping the future of our planet.

The chapters in this volume cover fundamental principles of green chemistry, eco-friendly synthesis methods, renewable feedstocks, energy-efficient processes, biodegradable materials, green solvents, and innovations in catalysis. Additionally, it delves into the integration of sustainable technologies in various sectors including agriculture, pharmaceuticals, energy, and waste management. The contributions offer interdisciplinary insights and practical approaches that aim to reduce environmental footprints and promote circular economy principles.

By emphasizing prevention of waste, reduction of hazardous substances, and life-cycle thinking, this book advocates for a paradigm shift in how chemistry and technology are taught, researched, and applied. It not only highlights the scientific and technical aspects but also underscores the ethical responsibility of the scientific community toward future generations.

We hope this volume inspires readers to contribute meaningfully to the field of sustainable science and serves as a valuable reference for future innovations. As we stand at the crossroads of environmental sustainability and *technological advancement, this book is both a call to action and a source of hope.*

Editors

Green Chemistry and Sustainable Technologies

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Ethnobotany, Phytochemistry, Therapeutic Potential, Current and Future Applications of *Cannabis sativa* L.

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Abstract

For more than a century, Cannabis was considered a narcotic and has been banned by lawmakers all over the world. In recent years, interest in this plant has increased due to its therapeutic potential, in addition to a very interesting chemical composition, characterized by the presence of an atypical family of molecules known as Phyto cannabinoids. With this emerging interest, it is very important to take stock of what research has been conducted so far on the chemistry and biology of Cannabis sativa. Cannabis is the most commonly used substance of abuse in the United States after alcohol and tobacco. Cannabis contains over 100 cannabinoids, of which Δ9-tetrahydrocannabinol and cannabidiol (CBD) are the most clinically relevant. Tetrahydrocannabinol is a partial agonist at CB1 and binds CB2 receptors. CBD has attracted significant interest due to its anti-inflammatory, anti-oxidative and anti-necrotic, protective effects. These biological proprieties are mainly due to the presence of bioactive metabolites represented by more than 550 different molecules. The historical, botanical, ethnopharmacological, chemical, bioinformatics and biological knowledge of Cannabis sativa from the earliest human communities to current medical applications, with a critical analysis of the multiple potential applications of cannabinoids in the contemporary scientific context. This paper presents the up-to-date reported investigations and opens many reflections and further research perspectives. Further clinical research is needed to investigate the potential therapeutic uses of this plant in specific medical conditions.

Keywords: *Cannabis sativa*, phytocannabinoids, cannabidiol, tetrahydrocannabinol, COVID-19, cannabis use disorder.

Introduction

According to the Global Burden of Disease 2019 study, more than 23.8 million people have cannabis use disorder globally, and cannabis use ranks third Worldwide among consumed substances of misuse, after alcohol and tobacco. Cannabis use disorder is more common in men and high-income countries. The prevalence of cannabis use disorder in the USA has been estimated to be around 6.3% in a lifetime and 2.5% for 12 months, and in Europe, around 15% of people aged 15-35 years reported cannabis use in the previous year. Of those using cannabis, one in three developed problems related to cannabis use that impaired functioning, and 10% used cannabis on a daily basis. Cannabis use disorder can affect up to 50% of people who use cannabis daily [1-3].

In Europe, over the past decade, self-reported use of cannabis within the past month has increased by almost 25% in people aged 15-34 years, and more than 80% in people who are 55-64 years. Cannabis or products containing tetrahydrocannabinol (cannabinoids) are widely available and have increasingly high tetrahydrocannabinol content. For instance, in Europe, tetrahydrocannabinol content increased from 6.9% to 10.6% from 2010 to 2019. Evidence has suggested that cannabis may be harmful, for mental and physical health, as well as driving safety, across observational studies but also in experimental settings. Conversely, more than a decade ago, cannabidiol was proposed as a candidate drug for the treatment of neurological disorders such as treatment-resistant childhood epilepsy. Furthermore, it has been proposed that this substance might be useful for anxiety and sleep disorders, and even as an adjuvant treatment for psychosis. Moreover, cannabis-based medications (i.e., medications that contain cannabis components) have been investigated as putative treatments for several different conditions and symptoms. The multifarious nature of cannabis's main active components, contrasting evidence from observational studies reporting detrimental effects of cannabis, and therapeutic findings of cannabis-based medicines from interventional studies, is reflected in different legislative approaches. Thus, in most countries' cannabis use is illegal, but in a small and growing number of countries and states cannabis is legally sold without the need for a medical prescription [3-6].

Cannabis sativa L., commonly known as cannabis, has been used for years for recreational and, more importantly, therapeutic or medicinal purposes. The cannabis plant contains a variety of phytochemicals, including flavonoids, terpenoids, phytocannabinoids, alkaloids, glycoproteins, and phytosteroids. The most well-known and studied phytochemicals in cannabis are the cannabinoids. Historically, cannabis has been valued for its pain-relieving, anti-inflammatory, and calming properties. Ancient civilizations like the Egyptians, Greeks, and Chinese medicines recognized their therapeutic potential. The discovery of the endocannabinoid system, which interacts with cannabis phytoconstituents, has scientifically explained how cannabis affects the human immune system, including the central nervous system [6,7].

Figure 1: Cannabis sativa L. plant

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Figure 2: Cannabis sativa a) General aspect; b) inflorescence; c) seed; d) leaf; e) stem

Geographic Distribution

Cannabis can grow in a vast majority of climates. From its region of origin, it appreciates calcareous and nitrogenous soils with a neutral or slightly acidic pH. This species originates from equatorial and subtropical regions, mainly from central Asia. However, this plant has a wide geographical distribution growing up in Canada, United States of America, Europe and Africa [2,8].

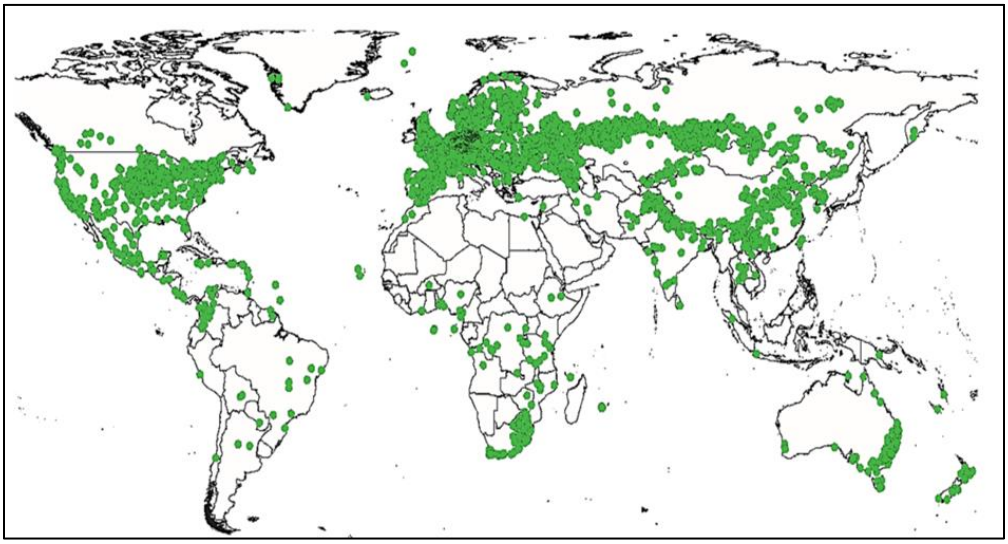


Figure 3: Geographic distribution of Cannabis sativa

Botanical Description

Cannabis sativa is an annual, usually dioecious plant belonging to the Cannabaceae family. It is now considered as the only species of the botanical

genus Cannabis but divided into several phenotypes that can be described as subspecies or varieties. C. sativa has the particularity of being a fast-growing plant with a fluted stem that can reach 1 to 4 m with a diameter ranging between 1 and 3 cm. The variation of height and diameter depends on the sub-species, environment, soil and climatic conditions. The seeds are smooth, greyish ovoid or spherical in shape, 2.5 to 3.5 mm long and 2.5 to 3 mm in diameter. Each seed contains two cotyledons rich in reserves (protein and oil), with an albumen considered particularly small compared to other plant species.
This plant is also characterized by long, fine flowers. It has glandular hairs that make it fragrant and sticky. At post-germination, young male and female plants cannot be distinguished. It is only during the last phase of growth, when flowers start appearing, that sex determination becomes possible. The Cannabis leaves are stipulate and opposite, with palmate (five to seven unequal), elongated and spiny segments with toothed margins. The root is taproot with a length of up to 30cm [9-12].

Phytochemistry

Numerous studies have shown the importance of Cannabis secondary metabolites as well as their roles. This plant offers a rich reservoir of bioactive molecules that can be used for the production of pharmaceutical, nutraceutical and cosmetic products.

Table 1: Chemical composition of C. sativa different plant parts

Plant part	**Metabolites**	**Compounds**
Leaf	Terpenes	β-Selinene Caryophyllene oxide α-Selinene (3.1± 0.6%)
	Polyphenols	Apigenin C-(hexoside-O-rhamnoside) Luteolin C-(hexoside-O-rhamnoside) Luteolin di-C-hexoside Luteolin glucuronide Apigenin di-C-hexoside
	Cannabinoids	CBD CBDV

		THC CBC Cannabidiol acid Cannabidiol THCA Cannabigerolic acid
	Alkaloids	Cannabisativine Cannabimine C Anhydrocannabisativine Aconitine Boldine Strychnine
	Stilbenoids	Canniprene (ND) Combretastatin B-2 (ND) α, α'-dihydro-3,4',5-trihydroxy-4,5'-diisopentenyl stilbene (ND)
Seed	Tocopherols	γ-tocopherol δ-tocopherol α-tocopherol β-tocopherol
	Polyphenols	Cannabisin A, B, C, D, E, F, G, I, M, N, O
	Phytosterols	β-Sitosterol Campesterol Stigmasterol
	Carotenoids	Lutein β-Carotene

Flower	Terpenes	(E)-Caryophyllene α-Humulene β-Selinene α-Selinene Caryophyllene oxide
	Cannabinoids	CBD THC CBDV CBTC

Cannabidiol (CBD); *cannabidivarine* (CBDV); *cannabicitran* (CBTC); *cannabichromene* (CBC); T*etrahydrocannabinol* (THC); *tetrahydrocannabinolic acid* (THCA); *cannabicitran* (CBTC).

The chemical investigations conducted in different Cannabis sativa plant parts shows that terpenes, polyphenols and cannabinoids are the main represented secondary metabolites. Terpenes are represented by more than 100 molecules identified in the flowers, roots and leaves, as well as in the secretory glandular hairs considered as the main production site. Furthermore, more than 20 polyphenols have been identified, and they are mainly flavonoids belonging to the flavone and flavonol subclasses. Concerning the cannabinoids, they are among the most represented metabolites of Cannabis despite being represented by less than 20 molecules. Cannabis seeds contain approximately 40% oil, 30% fibers and 25% proteins. Cannabinoids are a group of C21 or C22 terpenolic compounds mainly produced in Cannabis [13-18].

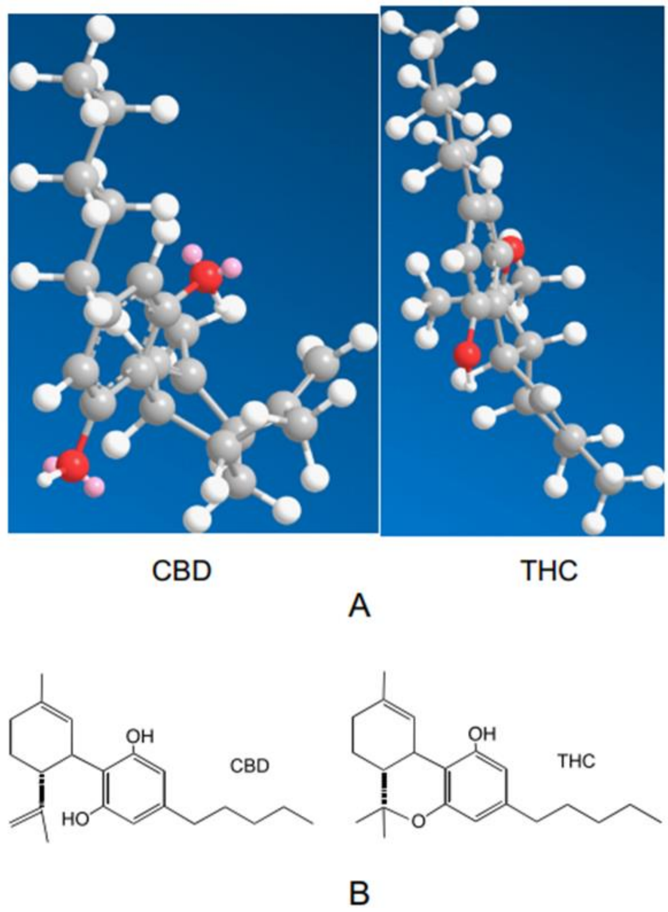


Figure 4: The minimal energy conformations of CBD and Δ9-tetrahydrocannabinol (THC) are shown in A. THC has a fairly planar conformation whereas CBD has a bent conformation. This difference results in different pharmacological profiles even though there is considerable structural overlap of both when viewed in a two-dimensional as shown in B.

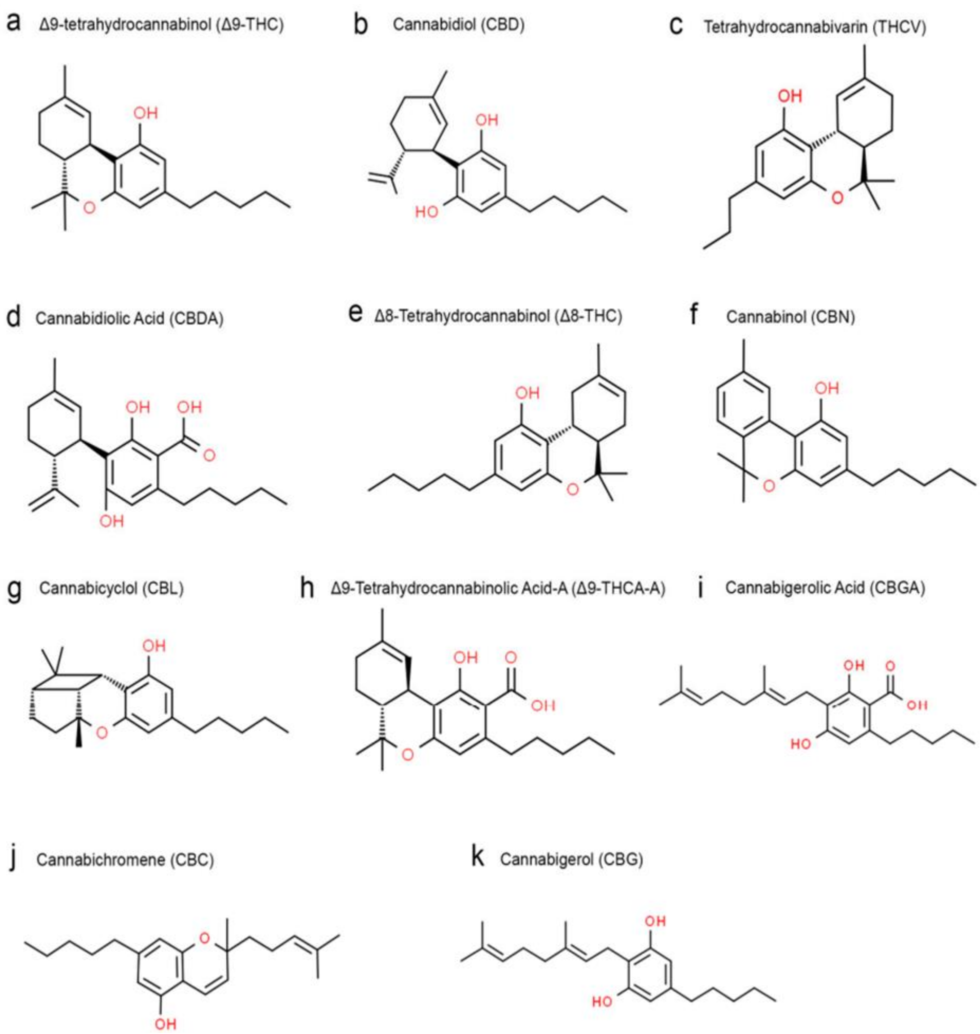


Figure 5: Structural formulas of different phytocannabinoid types from the cannabis plant

Traditional Uses

Cannabis sativa has been used in a wide variety of fields and showed a high usability potential with many applications including manufacturing of tools, construction, cosmetics, medication, shelter insulation, papermaking, human nutrition, animal feed, agrofuels, composite materials in association with plastics, etc [19-24].

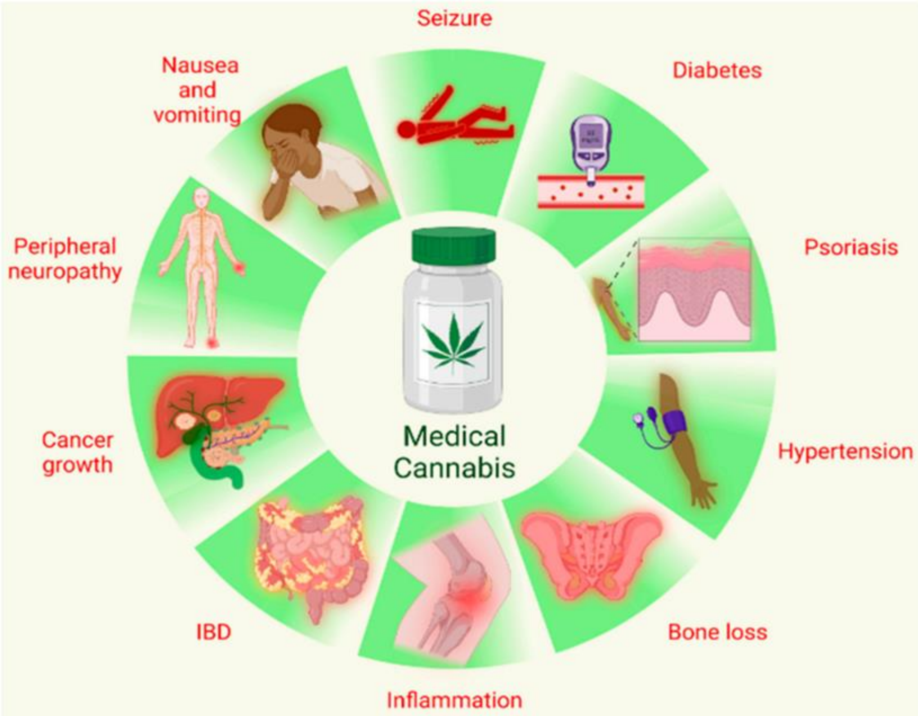


Figure 6: Medical uses of cannabis. Cannabis and different phytocomponents of cannabis, like THC and CBD, have been used for various therapies that include but are not limited to treating seizures and convulsions, vomiting and nausea, peripheral neuropathy and pain, and psoriasis; reducing cancer cell growth, bone loss, and inflammatory bowel disorder; being used as an anti-inflammatory and anti-hypertensive; and lowering blood glucose level.

Table 2: Traditional uses of different parts of C. sativa

Plant part	**Traditional use**
Leaf	Eczema, Bloating, cough, mucus, Central nervous system (CNS) depressant, gout, arthritic pain, Schizophrenia-like psychotic problems, Gastric disorders, Skin and subcutaneous tissue disorders, circulatory system and blood disorders.
Seed	Nutrition, Narcotic, painkiller, treat nausea and vomiting, stimulate appetite in AIDS patients, hepatitis C, anxiety, seizure, muscle relaxants, anticancer and weight control, Hair fortification, Analgesic, antiarthritic and antirheumatic.

Stem	Firewood or torch wood, Construction, materials, dress, papermaking, making ropes.
Root	Fever, Gout, arthritis, Joint pain, Skin burns, Inflammation, Childbirth, postpartum, hemorrhage, Erysipelas, toxins and infections.
Whole plant	Pain, gastric disorders, diabetes, scars and asthma.
Inflorescence	Sedative, dysentery, diarrhea and appetite loss.
Seed, flower	Hair care.
Leaf, inflorescence	Soporific, abortifacient.
Leaf, root	Cancer, hypertension, antidote to poison, itch, rheumatoid arthritis.

Medical Cannabis Laws

Federal regulations: In 1970, the Controlled Substances Act (CSA) consolidated all prior federal laws related to potential substances for abuse. These substances are classified by the CSA in 5 schedules according to their potential for abuse and medical efficacy. The CSA has classified cannabis, CBPs, and THC as Schedule I drugs, which is currently a source of conflict between federal and state cannabis regulations. Schedule I is the most restrictive classification and includes substances with no accepted medical use and the highest potential for abuse. Safety data on use of these substances under medical supervision are lacking. Some other substances classified as Schedule I include mescaline, psilocybin, heroin, methylenedioxymethamphetamine, and lysergic acid diethylamide. Because cannabis and cannabinoids are classified as Schedule I drugs, the ability to perform clinical trials with cannabis is considerably hindered. This classification also affects the ability of clinicians to prescribe cannabis and CBPs to their patients. Substances classified as Schedule I under the CSA can be legally possessed and/or dispensed only as part of federally approved research grants or programs. All involved manufacturers and distributors are required to obtain Schedule I drug-specific registration before initiating such research.

Moreover, cannabis for research must be obtained through a facility that is contracted with the National Institute on Drug Abuse. Currently, the only facility approved to provide cannabis for research purposes is the University of Mississippi. Because cannabis and its derivatives are classified as Schedule I drugs, physicians cannot formally prescribe these substances and may only recommend medical cannabis for their patients. According to a 2002 9th Circuit

Court of Appeals decision in Conant v Walters, physicians are protected against federal prosecution for communicating about medical cannabis use with their patients by the First Amendment of the US Constitution. The court also ruled that physicians should not be held liable for a patient's actions. Various state laws have permitted the distribution of cannabis through dispensaries, which conflicts with the CSA. The Agricultural Improvement Act of 2018 (i.e., the Farm Bill), signed into law by President Trump on December 20, 2018, legalized hemp at the federal level.

Hemp is a type of cannabis plant that contains low levels of THC-the psychoactive compound that produces the high associated with cannabis. Specifically, the Farm Bill defines hemp as the Cannabis sativa L. plant with a Δ9-THC concentration of 0.3% or less. The Farm Bill's legalization of hemp has had a notable effect on the CBD industry. CBD is a compound in hemp that has many potential health benefits. Before the Farm Bill was passed, CBD was classified as a Schedule I controlled substance and was thereby illegal to possess or sell. However, the Farm Bill's legalization of hemp has made it legal to manufacture and sell CBD products that are derived from hemp. The Farm Bill has had mixed reactions. Some have welcomed the change, arguing that it will provide consumers with access to a safe and effective natural remedy.

Others have expressed concern about the potential for CBD to be abused or misused. The US Food and Drug Administration (FDA) has not yet issued any regulations governing the sale of CBD products. Consequently, the CBD market is currently unregulated, which has led to concern about the quality and safety of some CBD products. The FDA is currently working to develop regulations for the sale of CBD products, and these regulations are expected to be finalized soon [25-30].

Table 3: Scheduled classes of controlled substances by the Controlled Substances Act of 1970

Schedule	Description	Example Substances
I	High abuse potential No accepted medical use	Heroin, LSD, MDMA, mescaline, psilocybin, marijuana/cannabis, cannabinoids, and peyote

II	High abuse potential Accepted medical use	Amphetamine, barbiturates, cocaine, fentanyl, methadone, and morphine
III	High abuse potential Accepted medical use	Ketamine, anabolic steroids, and buprenorphine
IV	High abuse potential Accepted medical use	Benzodiazepines, tramadol, and carisoprodol
V	High abuse potential Accepted medical use	Pregabalin, lacosamide, cannabis-derived pharmaceutical formulation (ie, Epidiolex)[a]

Other cannabidiol formulations remain Schedule I except for those derived from hemp, which were unscheduled after passage of the Agricultural Improvement Act of 2018 but are still regulated by the US Food and Drug Administration. Abbreviations: LSD-lysergic acid diethylamide; MDMA-methylenedioxymethamphetamine.

State Regulations

Medicinal use of cannabis was decriminalized for the first time by the state of California in 1996. The Compassionate Use Act of 1996 allowed patients and caregivers in California to cultivate and possess cannabis for medicinal use. State-regulated medical cannabis programs have since flourished due to limited interference by the federal government. Currently, 33 states and the District of Columbia have approved medicinal use of cannabis. A recent amendment to the US Consolidated Appropriations Act of 2018 restricts appropriation of federal funds to interfere with state-regulated implementation of medical cannabis laws [30-34].

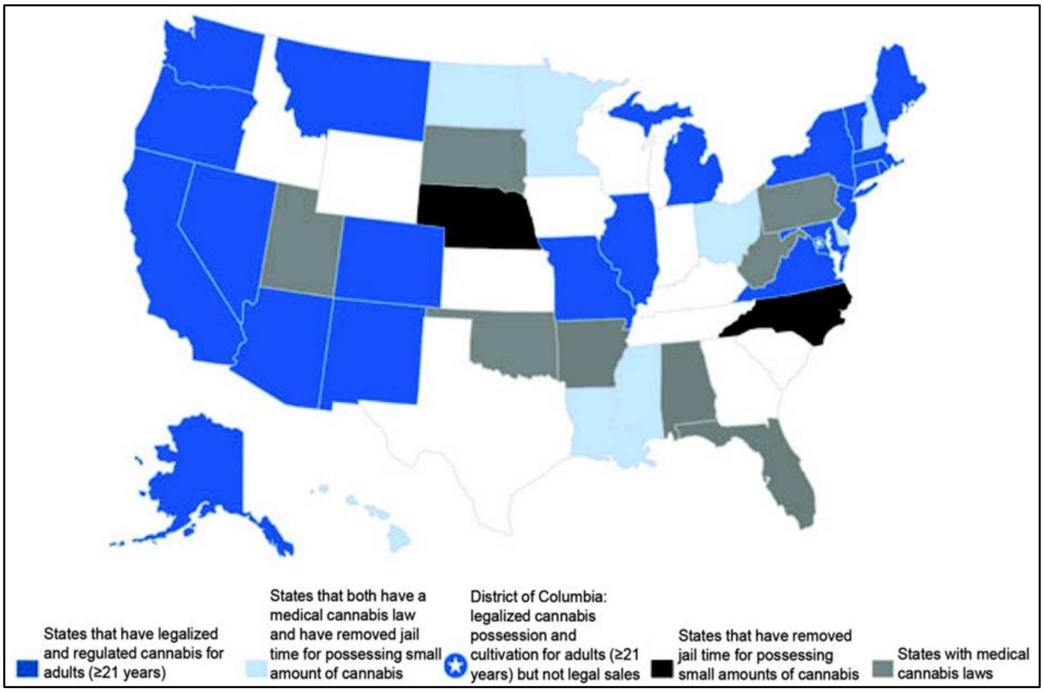
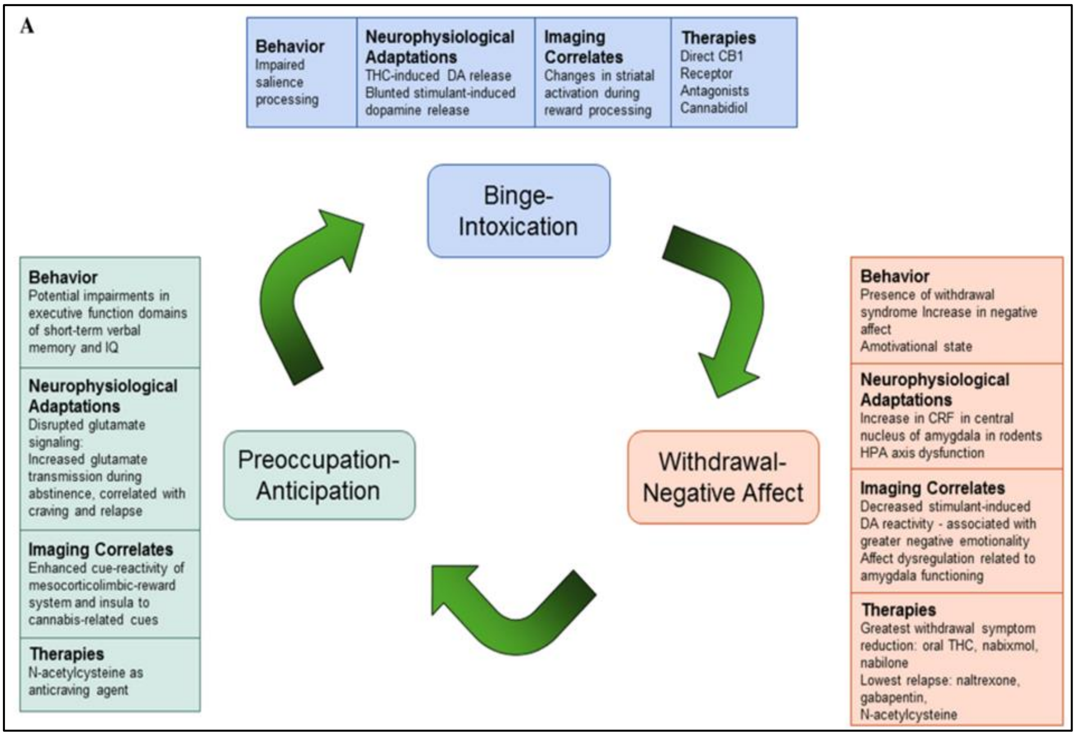


Figure 7: Current cannabis regulations among all US states



B

Stage	Changes	Summary
Binge-intoxication	Behaviour	THC-induced dopamine (DA) release disrupts incentive salience attribution.
	Neurophysiological Adaptations	Chronic THC downregulates CB1Rs and blunts striatal DA release in animals and humans.
	Imaging Correlates	Heightened, THC-induced ventral striatal activation to losses in monetary incentive delay (MID) task driven by chronic, relapsing cannabis users.
		Heightened, THC-induced ventral striatal activation to losses in MID task driven by chronic, relapsing cannabis users.
		It has been established that hyper-sensitivity to the rewarding properties of drugs contribute to positive reinforcement, which is driven by disrupted incentive salience processing.
	Therapies	Therapies with greatest reduction in binge-intoxication antagonize CB1Rs and include: rimonabant, which blocks the intoxicating and tachycardic effects of smoked cannabis.
		Partial agonists, which block the reinforcing effects of other drugs of abuse, have the potential to reduce the effects of cannabis intoxication.

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		Strains with higher CBD to THC ratios reduce the appetitive effects of cannabis compared to strains with lower CBD to THC ratios, suggesting CBD as a potential treatment for acute cannabis intoxication.
Withdrawal-negative affect	Behaviour	Presence of withdrawal syndrome marked by: irritability, anxiety decreased appetite, restlessness, and sleep disturbances.
		Increase in negative affect after prolonged cannabis use in adults and adolescents.
		Presence of a motivational state after prolonged cannabis exposure in rhesus monkeys and humans.
	Neurophysiological Adaptations	In rodents, cannabis withdrawal is associated with an increase in CRF in central nucleus of the amygdala.
		In human studies, cannabis withdrawal seems to be related to HPA axis dysfunction.
	Imaging Correlates	Chronic cannabis use is associated with decreased stimulant-induced DA reactivity that is associated with greater negative emotionality.
		Chronic cannabis use and cannabis withdrawal are associated with affect dysregulation related to amygdala functioning.

	Therapies	Therapies with the greatest reduction of withdrawal symptoms target CB1R and include: oral THC, nabixmol, nabilone all of which have a lower abuse potential than smoked cannabis.
		Therapies that have shown the greatest reduction of withdrawal symptoms and the lowest rates of relapse include naltrexone (a mu (μ) opioid receptor antagonist), gabapentin (a GABA-a receptor agonist), and N-acetylcysteine.
Preoccupation-anticipation	Behaviour	Preclinical and clinical models demonstrate impaired executive function in domains of memory and IQ result from acute and chronic cannabis use. Age-specific effects may be present.
		No significant long-term effects of adolescent cannabis use on executive function was found in several longitudinal co-twin cohort studies. Social and environmental factors may explain poor executive function among cannabis users.
	Neurophysiological Adaptations	Animal studies demonstrate increased glutamate transmission during drug self-administration while animals receiving glutamate receptor antagonists show reduced relapse rates.
	Imaging Correlates	Increased BOLD response to cannabis cues compared to naturally hedonic cues in mesocorticolimbic regions among cannabis users.

		Positive correlations between cue-induced self-rated craving for cannabis and BOLD responses within the mesocorticolimbic system and the insula.
	Therapies	N-acetylcysteine is a proposed anti-craving agent as it acts on the cysteine-glutamate antiporter to reduce glutamate neurotransmission that is upregulated during withdrawal. Preliminary clinical studies have demonstrated reduced craving and relapse rates in cannabis users.

Figure 8: A. Model of neurocircuitry and correlating disruptions in brain function and neurophysiology that contribute to behaviours underlying drug addiction. B. Summary of the changes in neurocircuitry associated with each stage

Drugs Based on *Cannabis sativa* L.

Due to the importance of the biological evaluation's findings, several Cannabis-based commercial pharmaceuticals have been produced. These products have many biological proprieties and were produced to treat a wide range of conditions. The first reported product has been commercialized under the name "marinol". This drug was developed 40 years ago, in 1985, by an American pharmaceutical company, and used dronabinol and synthetic THC as active agents. Likewise, "syndros" is another drug marketed in the USA in 2016 and it contains the same active ingredients. Both drugs are indicated for the treatment of severe nausea and vomiting related to cancer chemotherapy and AIDS-anorexia associated with weight loss.

Another active compound known as "nabilone" is used as ingredient of two drugs, "casamet" and "canemes". The "nabilone" is a synthetic analogue of THC approved by the U.S. Food and Drug Administration (U.S. FDA) for the treatment of chemotherapy and AIDS symptoms. Two other cannabinoids, namely "CBD" and "THC", are also used in two drugs commercialized under the name of Bourneville and used against two types of severe epilepsy (Lennox-Gastaut syndrome and Dravet syndrome), whereas Sativex, generally known as "nabiximols", is used to alleviate muscle spasms in multiple sclerosis disease [35-39].

Cannabis And Emerging Viral Diseases

With globalization, emerging and reemerging viral outbreaks are integral to our lives. COVID-19, caused by the severe acute respiratory syndrome coronavirus-2 (SARS-CoV-2), began in late 2019 in Wuhan, China, and has since developed into a global pandemic. Like other Coronavirus outbreaks, it affects the respiratory tract, leading to pneumonia-like symptoms with the potential to progress to severe acute respiratory distress syndrome (ARDS). The hyperinflammatory patterns of COVID-19 are like those of cytokine release syndrome (CRS). COVID-19 is driven by excessive inflammatory events, resulting in an increase in the white blood cell count but a decrease in CD4+ and CD8+ lymphocytes. This leads to an imbalance in the neutrophil-to-lymphocyte ratio.

After the establishment of infection, inflammatory cells enter the local site of infection, releasing pro-inflammatory cytokines, causing CRS at a very early stage of the disease. The anti-inflammatory properties of cannabis phytoconstituents could be used to prevent CRS. The endocannabinoid system controls the immune system by regulating the immune cell trafficking by acting through cannabinoid receptors. Therefore, by using phytocannabinoids such as THC and CBD, attenuation of the proliferation of lymphocytes and pro-inflammatory cytokines could be a possibility. Most of the severe outcomes of COVID-19 are due to CRS, and the use of medicinal cannabis could be used both as a preventative and therapeutic drug to mitigate CRS [40-44].

Cannabis Addiction or Cannabis Use Disorder

While cannabinoids have been widely researched and used for their anti-inflammatory and neuroprotective effects, it is essential to note that long-term exposure to cannabis smoke, THC, or CB1 receptor agonists may lead to the development of dependence, also known as cannabis use disorder (CUD). Cannabis withdrawal can also lead to bodily withdrawal signs such as abdominal constriction, wet-dog shakes, head shakes, and forepaw fluttering. Another notable adverse effect associated with cannabis withdrawal is anxiety-like behaviour that is orchestrated partly by the increased release of corticotropin-releasing hormone from the hypothalamus. Apart from these, published evidence in preclinical rodent models has shown cannabis and THC to significantly impair short- and long-term memory. THC weakens the release of acetylcholine in the hippocampus and represents a likely mechanism by which it impairs memory. It was shown that memory impairment due to THC could be reversed because, after four weeks of abstinence, THC-treated rodents had returned to their baseline state. Another study showed that a single dose of THC was strong enough to impair memory three weeks after administration.

Other studies have shown acute cannabis use to negatively affect emotional states and significantly impair cognitive processes and gross motor functions, including memory (retrieval, working, verbal) learning, executive functions, and various attentional tasks. Impairments in solving math problems, time perception, and gross and fine motor skills are commonly associated with adolescent cannabis use. Further, chronic cannabis use may lead to a motivational syndrome characterized by apathy, lack of motivation, and poor educational performance. Also, regular cannabis use alters the structure of the gray (cell bodies, dendrites, and synapses) and white matter (myelinated neuronal tracts). Furthermore, some evidence suggests that cannabis use may increase the size of subregions of the cerebellum and amygdala in adolescents. These changes are associated with poor executive functioning and internalizing problems.

However, most studies found that cannabis use decreased the volume of brain regions. In these studies, the most significant reduction in brain volume was detected in the orbitofrontal cortex, hippocampus, striatum, and amygdala. Interestingly, the degree to which the size of the hippocampus decreased depended on the amount of cannabis used and the extent of dependency. Heavy cannabis use is associated with an early onset of bipolar disorder, which shows increased severity and disability. In addition, heavy cannabis use by patients with bipolar disorder has also been linked to an increased tendency to commit suicide and develop manic symptoms [3,45-50].

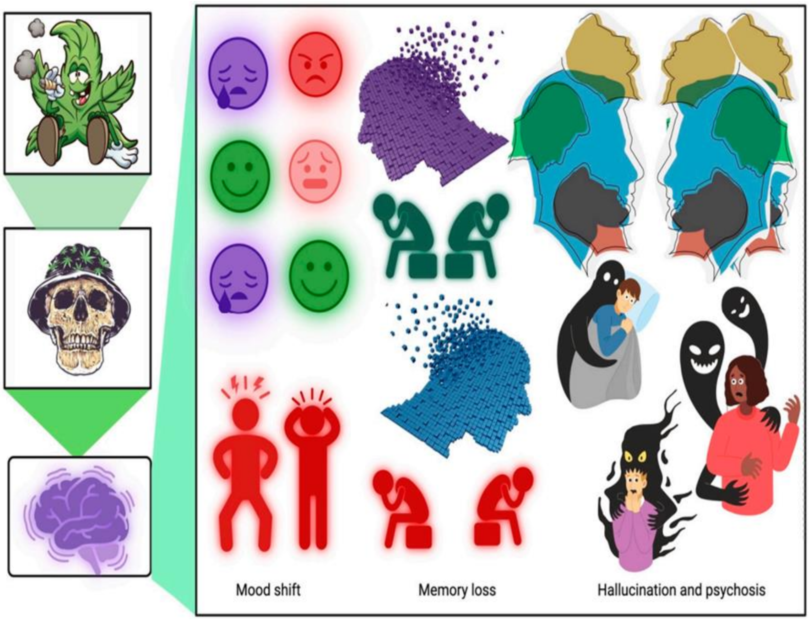

Figure 9: Impact of long-term recreational use of cannabis in the brain. Prolonged recreational cannabis use can lead to dependence and addiction, resulting in mood alterations, memory impairment, hallucinations, and even psychosis.

Future Prospectives

Cannabis has been used for centuries for various medicinal purposes. Recently, synthetic cannabinoids have been the primary source of medicinal Cannabis, and studies have found that THC is the primary source of adverse events. Unlike medical cannabis, recreational cannabis generally has a much higher THC content that can produce psychoactive effects. However, cannabinoids in combination (THC: CBD) may have the potential to be an alternative to opioids for chronic pain treatment. However, research is still needed on dosing and adverse reactions that the drug combination could have on the mind and body. CBD can mitigate some of the responses caused by THC. Many studies have highlighted the presence of endocannabinoids (ECBs) and cannabinoid receptors (CBRs) within bone and synovial tissues, underscoring their significant roles in bone metabolism and inflammation.

Preclinical investigations utilizing cannabinoid-based treatments in animal models have demonstrated the potential of cannabinoids to mitigate osteoarthritis (OA) progression, prevent osteoporosis (OP), and enhance fracture healing. These findings underscore the promising therapeutic prospects of CBs in addressing various human bone-related ailments. Further, these studies also emphasize the utility of cannabinoids in treating bone loss [88]. In the majority of the cases, the medicinal use of cannabinoids is not backed by strong scientific evidence, which warrants well-designed case-controlled studies for the establishment of its beneficial role as a therapeutic. Recently, the therapeutic potential of cannabinoids in alleviating neuroinflammation following traumatic brain injury (TBI) was highlighted. In addition to neuroinflammation, TBI patients also develop dysbiosis following neurotrauma leading to dysfunction of the microbiota-gut-brain axis (MGBA). Based on our recent findings we believe that phytocannabinoids may be an excellent therapeutic option to restore the function of the MGBA in TBI patients and prevent the progression of neurodegeneration and cardiovascular disease risk.

There are over 100 cannabinoids, each with potential benefits that remain to be discovered. Some other areas of interest regarding treatment with cannabinoids include epilepsy, psychotic disorders, anxiety, and sleep disorders. Data shows acute CBD administration decreases experimentally induced anxiety in healthy humans. CBD is now available as an FDA-approved drug (Epidiolex®) for use as an anticonvulsant for refractory epilepsy (Dravet syndrome or Lennox-Gastaut syndrome), particularly in the pediatric population.

Conclusion

Convincing or converging evidence supports that cannabis use is associated with poor mental health and cognition, increased the risk of car crashes, and can have detrimental effects on offspring if used during pregnancy. Cannabis use should be avoided in adolescents and young adults (when neurodevelopment is still occurring), when most mental health disorders have onset and cognition is paramount for optimising academic performance and learning, as well as in pregnant women and drivers. Conversely, cannabidiol could be considered a potential beneficial treatment option in epilepsy across age groups to reduce seizures. Cannabis based medicines could also be considered for chronic pain across different conditions, such as multiple sclerosis, spasticity in multiple sclerosis, for nausea and vomiting in people with mixed conditions and for sleep in cancer. However, clinical relevance must be considered before a possible incorporation into clinical guidelines; for example, including numbers needed to treat for benefit, risk to benefit ratios, comparative efficacy and safety with existing treatment options, and development of patient information concerning potential adverse events. Cannabidiol appears to be safe regarding psychiatric symptoms, but more research needs to be conducted before this drug can be recommended for the treatment of any psychiatric disorder. The remaining associations between cannabis and health outcomes are not supported by converging or convincing evidence. Law and public health policy makers and researchers should consider this evidence synthesis when making policy decisions on cannabinoids use regulation, and when planning a future epidemiological or experimental research agenda, with particular attention to the tetrahydrocannabinol content of cannabinoids. Future guidelines are needed to translate current findings into clinical practice, while involving stakeholders.

Furthermore, the relaxation of regulatory standards for therapeutic Cannabis and the conduct of more controlled clinical trials suggests that the Cannabis sativa plant has interesting therapeutic potential. Further clinical research is needed to investigate the potential therapeutic uses of this plant in specific medical conditions. Scientifically designed trials will help establish which of the cannabinoids produce the various beneficial effects described, or whether these are the result of a combination of cannabinoids. The research would also help to better characterize the adverse effects of each cannabinoid.

Conflicts of interest

The authors declare no conflict of interest.

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Antioxidant characteristics of different solvent extracts from *Prunus dulcis* L. shell

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Abstract

The extracts from almond shells, produced using different extraction solvents (80% methanol, 100% methanol, 80% ethanol, and 100% ethanol), were evaluated for their antioxidant activity and total phenolic (TP) content. Antioxidant activity (AA) was assessed by measuring reducing power, inhibition of linoleic acid peroxidation, and 2,2-diphenyl-1-picrylhydrazyl (DPPH) free radical scavenging capacity. The shell extracts exhibited significant total phenolic content, ranging from 1.36 to 7.21 mg of gallic acid equivalents (GAE) per 100g of dry matter. The reducing power (absorbance at 12.5 mg/mL extract concentration) ranged from 0.31 to 1.83, while inhibition of linoleic acid peroxidation and DPPH radical scavenging capacity varied from 38.22% to 82.80% and 12.15% to 57.90%, respectively. The results indicated significant ($p < 0.05$) variations depending on the extracting solvents and almond varieties tested. The efficacy of the solvents in extracting potent antioxidant components from almond shells followed this order: 80% methanol > 80% ethanol > 100% methanol > 100% ethanol. These findings highlight the potential of almond shells, an agricultural byproduct, for the extraction of antioxidants, which could be valuable in food preservation and pharmaceutical applications.

Keywords: Almond shell, solvent extraction, antioxidant components, total phenolics, linoleic acid peroxidation, 2,2-diphenyl-1-picrylhydrazyl (DPPH) radical.

Introduction

The shift away from synthetic antioxidants like BHA, BHT, and TBHQ in the food industry is due to concerns over their potential carcinogenic effects, as noted by Jeong et al. in 2004. In contrast, plant-derived natural antioxidants are becoming more popular because of their perceived anticarcinogenic properties and other health benefits, as highlighted by Iqbal et al. in 2007 and Sultana et al. in 2009. This trend reflects a growing preference for natural ingredients in food products, driven by consumer demand for safer and more health-conscious options. Plants are widely acknowledged as a significant source of natural antioxidants (Shahidi, 1997). Numerous studies and publications have demonstrated the antioxidant potential of plants, primarily attributed to their rich content of bioactive compounds, particularly phenolics (Shahidi, 1997; Buricova and Reblova, 2008; Sultana et al., 2009). The beneficial effects of dietary antioxidants like Vitamin C, tocopherols, and polyphenols on health are well-established, reinforcing the idea that diets abundant in fruits and vegetables are linked to a reduced risk of chronic diseases (Lana and Tijkskens, 2006). Regular consumption of nuts has also been associated with a lower risk of certain diseases, including cancer and diabetes (Pinelo et al., 2004). These health-promoting properties of nuts are likely connected to their content of bioactive compounds such as flavonoids, isoflavones, and other phenolics (Subashinee et al., 2002). Almonds (Prunus dulcis L.) are a notable member of the Prunus genus within the Prunoideae subfamily of the Rosaceae family. They are recognized for their nutritional and medicinal value. Almond consumption has been linked to lowering LDL cholesterol and reducing the risk of heart disease (Wijeratne et al., 2006). These health benefits are attributed to the antioxidant activity of vitamin E and monounsaturated fats, as well as phenolic compounds found in almonds, including catechin, protocatechuic acid, prenylated benzoic acids, and 2-prenyl-4-O-β-D-glucopyranosyl-oxy-4-hydroxybenzoic acid (Subashinee et al., 2002). There has been a growing interest in exploring the antioxidant potential of agricultural wastes (Bandoniene et al., 2000). For instance, Anwar et al. (2006) investigated the antioxidant efficacy of various agrowastes using different assays. Sultana et al. (2007) evaluated the antioxidant activity of corn cob extracts using multiple antioxidant models. Yen and Duh (2007) examined the antioxidant activity of methanolic extracts from peanut hulls across different cultivars. Additionally, Pinelo et al. (2004) assessed the antioxidant phenolics found in almond hulls and pine sawdust. The choice of extraction solvents significantly impacts the yield and antioxidant activity of extracted plant materials (Sultana et al., 2009; Anwar et al., 2010). Given almonds' potential as a source of bioactive compounds, examining the efficacy of various extraction solvents for recovering potent antioxidants from almond shells (which are often considered agrowaste) is valuable. The current study aims to assess how different extraction solvents affect the recovery of extractable components, phenolics, and antioxidant activity in the shells of two locally available almond varieties.

Materials and Methods

Collection of Samples

Almond samples, identified as varieties katha (thick shell) and kaghazi (thin shell), were obtained from a local dry fruit market in Pune Maharashtra. The shells were manually removed and then dried under ambient conditions before being used for extraction.

Chemicals and Reagents

The reagents used in a study, indicating that all were of analytical grade, primarily sourced from Merck or Sigma. Specific chemicals like DPPH, linoleic acid, BHT, and Folin-Ciocalteu reagent were obtained from Sigma Chemicals Co., while other analytical-grade chemicals, including anhydrous sodium carbonate, sodium hydroxide, sodium nitrite, ferrous chloride, ammonium thiocyanate, potassium dihydrogen phosphate and dipotassium hydrogen phosphate, were purchased from Merck.

Extracting Solvent System

The dried almond shell samples were finely ground using a commercial blender (TSK-949, Westpoint, France). The powder that passed through an 80-mesh sieve was selected for extraction. Four solvent systems were used for extraction: 80% methanol (methanol: water, 80:20 v/v), pure methanol, 80% ethanol (ethanol: water, 80:20 v/v), and pure ethanol.

Extraction of Antioxidant Components from Almond Shells

The ground almond shell material (20 g) was extracted with 200 mL of each solvent (80% methanol, 100% methanol, 80% ethanol, and 100% ethanol) at room temperature for 6 hours using an orbital shaker (Gallenkamp, UK). The mixture was then filtered through Whatman No. 1 filter paper to separate the residues, which were re-extracted with fresh solvent. The combined extracts from both extractions were concentrated by removing the solvent under vacuum at 45°C using a rotary evaporator (EYELA, SB-651, Rikakikai Co. Ltd., Tokyo, Japan). The resulting semi-solid crude concentrated extracts (CCE) were weighed to determine the yield and stored at -4°C in a refrigerator until further analysis (Sultana et al., 2009).

Evaluation Of Antioxidant Activity of Almond Shell Extract

The total phenolics (TP) content was estimated colorimetrically using the Folin-Ciocalteu reagent, following the method described by Sultana et al. (2009). In this procedure, 50 mg of crude extract was mixed with 0.5 mL of Folin-Ciocalteu reagent and 7.5 mL of deionized water. After allowing the mixture to sit at room temperature for 10 minutes, 1.5 mL of 20% sodium carbonate (w/v) was added. The mixture was then heated in a water bath at 40°C for 20 minutes, followed by cooling in an ice bath. The absorbance was measured at 755 nm using a spectrophotometer (U-2001, Hitachi Instruments Inc., Tokyo, Japan). The TP content was quantified using a gallic acid standard calibration curve (R^2 = 0.9984), and the results were expressed as gallic acid equivalents (GAE) per 100 g of dry matter.

The 2,2–diphenyl–1-picrylhydrazyl (DPPH) free radical scavenging activity of the extracts was evaluated using the method previously described by Iqbal et al. (2005). Briefly, 1.0 mL of extract containing 25 µg/mL of dry extract mass in methanol was mixed with 5.0 mL of freshly prepared DPPH solution (0.025 g/L). The absorbance of the reaction mixture was measured at 515 nm using a spectrophotometer at various time intervals (0.5, 1.0, 2.0, 5.0, and 10.0 minutes). The absorbance recorded at the 5th minute was used to compare the radical scavenging activity of the extracts. The percentage of DPPH radical scavenging activity was calculated using the following equation:

I% = 100− (A blank – A sample) \ A blank

In this equation A blank denotes the absorbance of control while A sample is the absorbance of the test reaction mixture.

Antioxidant activity determination in linoleic acid system

The antioxidant activity of the almond shell extracts was also assessed by evaluating their ability to inhibit linoleic acid peroxidation, as described by Iqbal et al. (2005). To do this, 5 mg of the extract was added to a solution containing 0.13 mL of linoleic acid, 10 mL of 99.8% ethanol, and 10 mL of 0.2 M sodium phosphate buffer (pH 7). The mixture was diluted to a final volume of 25 mL with distilled water and incubated at 40°C for up to 360 hours. The extent of oxidation was determined by measuring the peroxide value using the thiocyanate method, as outlined by Yen et al. (2000). In this method, 10 mL of 75% ethanol (v/v), 0.2 mL of a 30% (w/v) aqueous ammonium thiocyanate solution, 0.2 mL of the sample solution, and 0.2 mL of ferrous chloride ($FeCl_2$) solution (20 mM in 3.5% HCl) were added sequentially to a volumetric flask. After stirring for 5 minutes, the absorbance of the reaction mixture was measured at 500 nm using a spectrophotometer. A control sample containing all the reagents except the test extract was processed under the same conditions. Butylated hydroxytoluene (BHT), a synthetic antioxidant, was used as a positive control. The percentage inhibition (I) of linoleic acid peroxidation was calculated using the following equation:

(% I) = 100 – [(Abs. increase of sample at 360 h / Abs. increase of control at 360 h) / 100]

Determination Of Reducing Power

The reducing power of the almond shell extracts was evaluated using a modified procedure based on Yen et al. (2000). Extracts, with concentrations ranging from 2.5 to 10.0 mg/mL, were mixed with 5.0 mL of 0.2 M sodium phosphate buffer (pH 6.6) and 5.0 mL of 1.0% potassium ferricyanide solution. The mixture was incubated at 50°C for 20 minutes. Following incubation, 5.0 mL of 10% trichloroacetic acid was added, and the mixture was centrifuged at 1000 × g for 10 minutes at 5°C using a refrigerated centrifuge (CHM-17; Kokusan Denki, Tokyo, Japan). The upper layer (5.0 mL) was decanted and further diluted with 5.0 mL of distilled water, followed by the addition of 1.0 mL of 0.1% ferric chloride solution. The absorbance of the resulting mixture was measured at 700 nm using a spectrophotometer. The reducing power of the extracts was expressed based on the absorbance values obtained.

Statistical Analysis

Three samples from each almond variety were assayed and analyzed individually in triplicate, and the data were reported as mean ± SD ($n = 3 \times 3 \times 1$). The data were analyzed using Minitab 2000 Version 13.2 statistical software (Minitab Inc., Pennsylvania, U.S.A) at a 5% significance level.

Results and Discussion

Antioxidant Yield

The percentage yield and total phenolic content of shell extracts from the tested almond varieties (thick shell and thin shell) are shown in Table 1. The antioxidant components extracted from almond shells using various solvents—80% methanol, 100% methanol, 80% ethanol, and 100% ethanol—ranged from 2.08% to 8.92%, indicating significant differences among the solvents ($P > 0.05$). The aqueous ethanol (80%) extract yielded the highest amount of extract for both shell varieties, with yields of 6.65% for the thick shell and 8.92% for the thin shell. This suggests that the antioxidant compounds in almond shells are more soluble in aqueous ethanol and aqueous methanol compared to pure solvents. The percentage yield of antioxidant components in our study was higher than those previously reported (0.25% to 4.46%) by Pinelo et al. (2004) for almond hulls using ethanol, methanol, and water.

Differences in the yield of extracts from almond shells may be attributed to the varying polarities of the solvents used, as well as the chemical composition of the extractable components (Sfahlan et al., 2009). According to the present results, the effectiveness of different solvents in extracting antioxidant components from almond shells followed this order: 80% ethanol > 80% methanol > 100% ethanol > 100% methanol.

Total Phenolic Contents (TPC)

Interest in plant phenolics has significantly increased due to their notable free radical scavenging activity (Sultana and Anwar, 2008). The total phenolic content (TPC) in almond shell extracts was determined using the Folin-Ciocalteau method, with results expressed as gallic acid equivalents per unit of dry matter. This colorimetric method was selected for its effectiveness, simplicity, and rapidity in quantifying total phenolics.

The total phenolic content (TPC) of pure and aqueous methanolic and ethanolic extracts from thick and thin shell almonds is presented in Table 1. The TPC varied from 1.36 to 7.21 gallic acid equivalents (GAE) mg/g of dry matter, showing significant variation among solvents and between the almond varieties tested. The phenolic contents observed in this study were consistent with the findings of Pinelo et al. (2004), who reported TPC in ethanol extracts ranging from 2.31 to 7.21 mg GAE/g and in methanol extracts ranging from 1.06 to 4.12 mg GAE/g from almond hulls. In contrast, Sfahlan et al. (2009) reported much higher TPC values, ranging from 18.4 to 62.7 mg GAE/g, in methanol extracts from various almond shell varieties.

When comparing the two almond varieties, the thin shell variety exhibited relatively higher TPC values compared to the thick shell variety. For both varieties, aqueous methanol and aqueous ethanol extracts yielded a greater number of total phenols. This finding is supported by existing literature, which has demonstrated that aqueous methanol and ethanol are effective solvents for extracting phenolic compounds from various plant matrices (Siddhuraju and Becker, 2003; Sultana et al., 2009; Sultana and Anwar, 2008; Anwar et al., 2010).

Table 1. Yield (g/100g of dry weight) and total phenolic contents (GAE) mg/g of dry matter) of solvents extracts from almond shell.

Extract	**Percentage yield (g/100g of dry matter) Total phenolic contents (GAE) mg/g of dry matter)**			
	Thick Shell	**Thin Shell**	**Thick Shell**	**Thin Shell**
100% methanol extract	2.50 ± 0.30	2.08 ± 0.05	2.07 ± 0.30	3.78 ± 0.05
80% methanol extract	5.40 ± 0.21	3.36 ± 0.13	2.26 ± 0 .21	7.21 ± 0.20
100% ethanol extract	3.30 ± 0.32	3.87 ± 0 .16	1.36 ± 0.01	2.31 ± 0.50

80% ethanol extract	6.65 ± 0.43	8.92 ± 0.40	1.47 ± 0.03	2.87 ± 0.20

Values are mean ± SD of three samples analysed individually in triplicate ($p < 0.05$).

Table 2. DPPH radical scavenging capacity and inhibition of linoleic acid peroxidation of different solvent extracts from almond shell.

Extract	**% DPPH radical scavenging activity**		**% Inhibition of linoleic acid peroxidation**	
	Thick Shell	**Thin Shell**	**Thick Shell**	**Thin Shell**
100% methanol extract	17.64 ± 0.28	37.01 ± 0.70	68.15 ± 1.30	64.14 ± 2.90
80% methanol extract	18.22 ± 0.21	57.90 ± 0.58	82.80 ± 0.90	76.25 ± 2.00
100% ethanol extract	14.92 ± 0.45	15.32 ± 0.73	38.22 ± 1.90	61.80 ± 1.80
80% ethanol extract	12.15 ± 0.34	36.22 ± 0.96	73.25 ± 2.10	58.20 ± 1.40

Values are mean ± SD of three samples analyzed individually in triplicate ($p < 0.05$).

DPPH Radical Scavenging Assay

DPPH (2,2-diphenyl-1-picrylhydrazyl) is a stable organic free radical with a violet color and an absorption maximum around 515 to 528 nm. When it accepts a proton from hydrogen donor substances, such as phenolics, it loses its chromophore and turns yellow. An increase in the concentration or hydroxylation degree of phenolic compounds enhances the DPPH free radical scavenging capacity and thus the antioxidant activity (Sultana and Anwar, 2008). The percentage of DPPH free radical scavenging activity for various almond shell extracts, influenced by the extracting solvent, is shown in Table 2. Absorbance values were recorded at time intervals from 0.5 to 10 minutes after the reaction started. Scavenging activity was similar at the beginning of the reaction but changed over time, stabilizing by the 10th minute. Significant differences ($p < 0.05$) in DPPH scavenging capacity among different solvent extracts were observed at the 5th minute of the reaction.

A higher percentage of DPPH• scavenging capacity correlates with increased antioxidant activity of the extracts (Sultana et al., 2009). The DPPH• scavenging activity for almond extracts varied widely, ranging from 12.15% to 18.22% for the thick shell and 15.32% to 57.9% for the thin shell extracts. The highest scavenging activity was observed in 80% methanol extracts from both varieties, indicating the greater efficacy of this solvent in extracting potent radical scavengers. This scavenging activity likely relates to the presence of phenolic compounds, as determined in the related assays. The results of this study are consistent with those reported by Pinelo et al. (2004), which found DPPH• scavenging activities ranging from 2.15% to 36.21% in pure ethanol extracts and 14.92% to 58.05% in pure methanol extracts of almond hull. The scavenging activity in this study was significantly affected ($P < 0.05$) by the extraction solvents used.

Antioxidant Activity in Linoleic Acid System

The antioxidant activity of almond shell extracts in this study was evaluated by measuring the percentage inhibition of linoleic acid oxidation. Linoleic acid (C18:2), a polyunsaturated fatty acid, forms peroxides upon oxidation. These peroxides then oxidize ferrous (Fe^{2+}) ions to ferric (Fe^{3+}) ions, which form a complex with thiocyanate (SCN). The concentration of this complex is estimated colorimetrically by measuring absorbance at 500 nm. Higher peroxide formation results in greater absorbance, indicating lower antioxidant activity.

The results for the percentage inhibition of linoleic acid peroxidation, after an incubation period of 360 hours, are shown in Table 2. Butylated hydroxytoluene (BHT), a synthetic antioxidant, was used as a positive control to compare the antioxidant activity of almond shell extracts. The extracts from both almond varieties demonstrated significant inhibition of peroxidation, ranging from 38.22% to 82.80% for the thick shell and 58.20% to 76.25% for the thin shell. As anticipated, the aqueous (80%) methanol and aqueous (80%) ethanol extracts were more effective in inhibiting peroxidation. Antioxidant activity, as measured by this test, varied significantly among the varieties and solvents tested ($P < 0.05$).

Table 3. Reducing power of different extracts from almond shell.

Conc. mg/mL	**Extract**								
	100% Methanol		**80% Methanol**		**100% Ethanol**		**80% Ethanol**		**BHT**
	Thick Shell	**Thin Shell**	**Thick Shell**	**Thin Shell**	**Thick Shell**	**Thin Shell**	**Thick Shell**	**Thin Shell**	
2.5	0.31 ± 0.01	0.40 ± 0.01	0.55 ± 0.01	0.55 ± 0.01	0.08 ± 0.01	0.08 ± 0.01	0.21 ± 0.01	0.20 ± 0.01	0.74 ± 0.04
5	0.46 ± 0.01	0.46 ± 0.01	0.62 ± 0.02	0.61 ± 0.02	0.12 ± 0.02	0.12 ± 0.02	0.37 ± 0.08	0.37 ± 0.08	0.94 ± 0.05
7.5	0.59 ± 0.04	0.50 ± 0.04	0.73 ± 0.03	0.72 ± 0.03	0.27 ± 0.02	0.27 ± 0.02	0.38 ± 0.10	0.38 ± 0.10	1.13 ± 0.06
10	0.92 ± 0.05	0.90 ± 0.05	0.85 ± 0.03	0.84 ± 0.03	0.29 ± 0.04	0.28 ± 0.04	0.41 ± 0.11	0.41 ± 0.11	1.53 ± 0.08
12.5	1.54 ± 0.06	1.44 ± 0.06	1.83 ± 0.04	1.82 ± 0.04	0.32 ± 0.04	0.31 ± 0.04	0.43 ± 0.13	0.53 ± 0.13	1.70 ± 0.09

Values are mean ± SD of three samples analysed individually in triplicate ($P < 0.05$).

Reducing Power of Extracts

Measuring the reducing potential is a valuable method for studying key aspects of antioxidant activity in plant extracts. In this method, ferric ions are reduced to ferrous ions, resulting in a color change from yellow to bluish-green. The intensity of the color, and thus the absorbance, directly correlates with the reducing potential of the compounds present in the reaction medium. Greater color intensity indicates higher antioxidant activity (Sultana and Anwar, 2008). Table 3 presents the reducing potential of almond shell extracts from two varieties, obtained using aqueous and pure alcohols. The reducing potential of the extracts increased in a concentration-dependent manner over the range of 2.5 to 12.5 mg/mL. At a concentration of 12.5 mg/mL, the reducing potential ranged from 0.32 to 1.83 absorbance units. The highest reducing potential was observed in the 80% methanolic extracts, with values of 1.83 for the thick shell and 1.82 for the thin shell. Statistical analysis revealed significant variation in reducing potential based on the extraction solvent and almond variety tested. Sfahlan et al. (2009) reported a lower reducing power for almond shell extracts using methanol, ranging from 0.151 to 0.228, compared to the values found in the present study. Variations in the reducing potential of plant extracts may be attributed to differences in the genetic makeup of almond varieties, as well as factors such as harvest maturity and processing conditions (Sultana and Anwar, 2008; Sultana et al., 2009; Anwar et al., 2010).

Based on the results of this study, it can be concluded that the antioxidant potential of almond shell extracts varied significantly depending on the almond varieties and the extraction solvents used. Aqueous (80%) methanol emerged as the most effective solvent for extracting potent antioxidant components from almond shells. This investigation highlights the potential of almond shells as an economical raw material for extracting valuable antioxidants.

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Zero Waste Technologies and Industrial Symbiosis

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Abstract

The fast-paced world of industrialization has brought about a surge in waste production, depletion of resources, and harm to our environment. In light of these challenges, innovative approaches like Zero Waste technologies and Industrial Symbiosis (IS) have emerged as essential components of sustainable industrial growth. Zero Waste technologies aim to create systems that eliminate waste by maximizing material usage, improving resource efficiency, and encouraging practices like reuse, recycling, and recovery throughout a product's life cycle. Meanwhile, Industrial Symbiosis fosters collaboration between industries, allowing one industry's waste or by-products to be used as raw materials for another, which helps create closed-loop systems and reduces the reliance on new resources.

This chapter delves into how these two complementary frameworks can work together as a comprehensive strategy to promote circular economy principles and achieve lasting environmental sustainability. Through a mix of case studies, theoretical insights, and policy evaluations, the research illustrates how Zero Waste objectives can inspire the development of symbiotic industrial networks, while IS mechanisms offer the practical infrastructure needed to implement Zero Waste strategies on a larger scale. Advances in waste valorization, energy recovery, and digital platforms for resource sharing further bolster this integration.

Additionally, the chapter examines the importance of government regulations, collaboration among stakeholders, and life cycle thinking in expanding these

practices worldwide. Real-life examples, such as eco-industrial parks and green chemistry initiatives, showcase the real environmental and economic advantages that can be gained through this synergy. Ultimately, the combined use of Zero Waste technologies and Industrial Symbiosis offers a powerful pathway to reduce ecological footprints, conserve limited resources, and reimagine industrial systems as regenerative and sustainable networks.

Keywords: Zero Waste, Industrial Symbiosis, Sustainability, Circular Economy, Resource Efficiency, Waste Management

Introduction

Given the growing global issues of resource depletion, climate change, and environmental degradation, the linear "take-make-dispose" model that characterizes the modern industrial paradigm has become more and more unsustainable. According to Geissdoerfer et al. (2017), traditional industrial systems are mainly inefficient, producing enormous amounts of waste and pollution while putting a great deal of strain on limited natural resources. Alternative frameworks based on sustainability have become more popular in response to these urgent problems. Zero waste technologies and industrial symbiosis are two of the most significant of these, as they complement the circular economy's overarching goal.

The idea behind zero waste technologies is all about cutting out waste right from the design and system level. By implementing closed-loop material cycles, cleaner production methods, and creative product designs, zero waste strategies aim to completely eliminate waste instead of just dealing with it after it's been created (Zaman, 2015). These technologies inspire industries and communities to shift towards a model where everything is recycled, composted, or reused, rendering the concept of "waste" meaningless. According to the Zero Waste International Alliance (ZWIA), zero waste means "conserving all resources through responsible production, consumption, reuse, and recovery of products, packaging, and materials without burning and with no harmful discharges into land, water, or air that could harm the environment."

While zero waste is all about cutting down on waste within individual systems or organizations, industrial symbiosis takes a step back to look at the bigger picture. It's all about different industries that usually operate separately coming together to swap materials, energy, water, and by-products in a way that benefits both the economy and the environment (Chertow, 2000). A prime example of this can be seen in Kalundborg, Denmark, where a network of businesses—including a power plant, a pharmaceutical company, an oil refinery, and a municipal utility—collaborate to share resources like steam, water, and waste heat (Ehrenfeld & Gertler, 1997). This kind of teamwork not only cuts down on the need for new materials but also helps lower emissions and waste, paving the way for a more resilient and sustainable industrial ecosystem.

The connection between zero waste and industrial symbiosis is incredibly impactful. When these two ideas come together, they form a robust framework that tackles sustainability on both small (like within a single organization) and large (across multiple organizations or regions) scales. For example, a factory focused on zero waste might cut down on scrap materials, while industrial symbiosis helps ensure that any by-products that can't be avoided are utilized by other industries instead of being thrown away. This kind of integration is a key part of the circular economy, which promotes the ongoing use of resources and aims to lessen environmental impacts throughout the life cycles of products (Murray, Skene, & Haynes, 2017).

Making zero waste technologies and industrial symbiosis work effectively depends not just on new technologies but also on having supportive policies, engaging stakeholders, and providing education. Government incentives, regulatory frameworks, and partnerships between public and private sectors are all essential in helping shift from linear to circular systems (Geng et al., 2010). Moreover, nurturing a culture of sustainability within organizations and among consumers is vital for the long-term success of these efforts.

In summary, zero waste technologies and industrial symbiosis are game-changing strategies in the quest for sustainable development. When used together, they pave the way for reducing environmental impacts, optimizing resource use, and building long-term economic resilience. As global challenges grow more pressing, embracing these integrated systems is not just a good idea; it's essential for fostering a regenerative and circular industrial future.

Zero Waste Techniques

Zero waste techniques are all about finding smart strategies and technologies that help us cut down on waste at every stage of a product's life—from the initial design and manufacturing to how we use and eventually dispose of it. The zero-waste philosophy is rooted in being resource-efficient, thinking about the entire lifecycle, and avoiding harm to our environment. It encourages us to move away from just dealing with waste at the end (like throwing things in landfills or burning them) and instead focus on proactive, systemic methods that keep materials in use and lessen our dependence on new resources (Zaman, 2015).

Here Are Some Key Zero Waste Techniques to Consider

1. **Eco-Design and Sustainable Product Development:** At the heart of zero waste is the idea of creating products that have minimal impact on the environment. This means choosing materials that can be recycled or biodegraded, using less material overall, designing products that can be easily

taken apart, and steering clear of harmful substances. For instance, cradle-to-cradle design principles ensure that materials can be reused endlessly without losing their quality (Braungart & McDonough, 2009).

2. **Cleaner Production:** Cleaner production methods focus on cutting down waste and emissions right from the source by fine-tuning industrial processes. This can involve changing manufacturing practices to use fewer raw materials, boosting energy efficiency, and avoiding toxic inputs (UNEP, 2010). Examples include closed-loop water systems, recovering heat, and redesigning processes to minimize scrap.
3. **Source Separation and Segregation of Waste:** To make zero waste systems work effectively, waste needs to be sorted right where it's generated. This allows for better recycling and composting. In many cities, mandatory source separation programs for organic materials, plastics, metals, and paper have greatly decreased reliance on landfills (Zaman & Lehmann, 2011).
4. **Extended Producer Responsibility (EPR):** EPR policies hold manufacturers accountable for the entire lifecycle of their products, including what happens after consumers are done with them. This encourages producers to create items that are easier to reuse or recycle and to invest in programs that allow for product returns (OECD, 2016).

Figure 1: Zero Waste Techniques

Industrial Symbiosis

Industrial symbiosis (IS) and green chemistry share a common goal: to cut down on waste, boost resource efficiency, and lessen environmental impact through teamwork and systematic strategies. Green chemistry is all about crafting safer chemical processes and products that tackle pollution right at the source, following principles like minimizing waste, enhancing energy efficiency, and opting for renewable feedstocks (Anastas & Warner, 1998). On the flip side, industrial symbiosis focuses on different industries working together to make the most of each other's by-products, waste energy, and resources, creating a circular flow of materials across various sectors (Chertow, 2000). When these two concepts come together, they pave the way for eco-industrial networks where innovations in green chemistry—such as safer solvents or atom-efficient reactions—can be scaled up and made economically feasible through collaborative partnerships. For instance, a company's waste solvent could serve as a valuable resource for another company's green synthesis process, effectively closing resource loops and reinforcing the idea of waste prevention. This collaboration pushes industries beyond just managing pollution at the end of the process, moving toward a more proactive approach to sustainable manufacturing. Additionally, blending IS with green chemistry boosts resilience by decentralizing resource use and encouraging a variety of material inputs (Yeo, Ong, & Nee, 2019). The shared focus on systems thinking and sustainability in both approaches makes their integration a powerful strategy for transforming traditional linear industrial models into regenerative and circular systems.

The core principles of IS include:

- **By-product Synergy:** Turning the waste of one company into a resource for another. For example, fly ash from a power plant can be repurposed in cement production.
- **Energy Cascading:** Capturing and reusing thermal energy across different facilities. Waste heat from one facility can be utilized to warm another.
- **Shared Utility Systems:** Industrial clusters can jointly invest in and maintain infrastructure for water treatment, steam generation, or material storage.

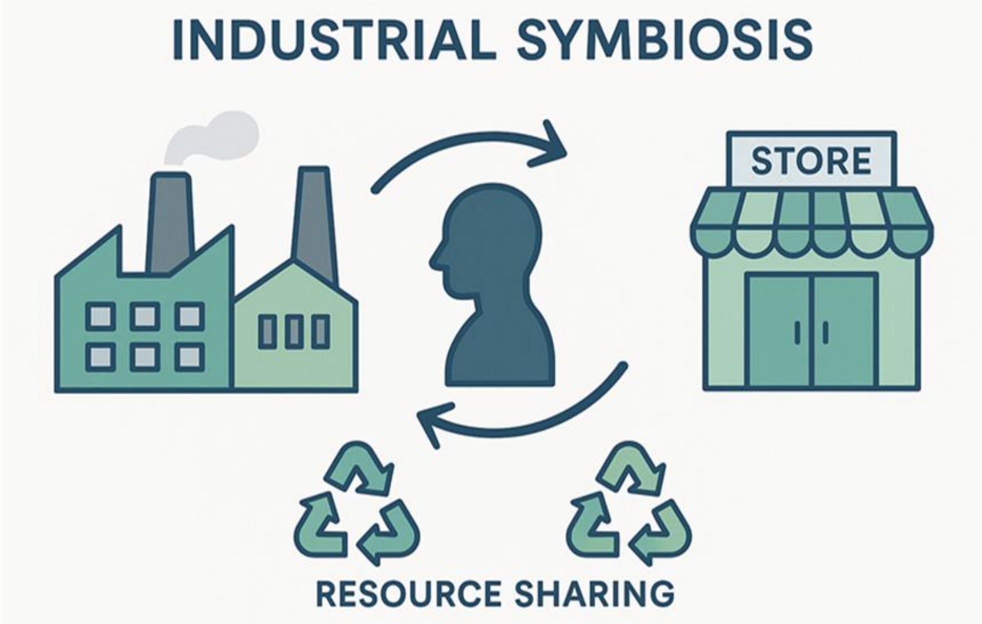

Figure 2: Industrial Symbiosis

A great example of this concept is the Kalundborg Symbiosis in Denmark, where a coal-fired power plant, a pharmaceutical company, a refinery, and several other businesses work together in a symbiotic relationship. By sharing resources like steam, sludge, fly ash, and wastewater, Kalundborg has managed to lessen its environmental impact while also boosting economic benefits (Ehrenfeld & Gertler, 1997). Recently, the field of industrial symbiosis has seen the rise of digital platforms that make it easier for companies to exchange by-products and connect with one another. Tools like material flow mapping and industrial ecology simulation models are helping to streamline resource flows and uncover new opportunities for collaboration (Fraccascia et al., 2021; Yeo et al., 2019; D. Lombardi, et al. 2012).

Integration of Zero Waste and Industrial Symbiosis

Industrial symbiosis connects regional and inter-organizational networks, going beyond zero waste techniques, which seek to reduce and eradicate waste at the organizational level. The foundation for a major change in resource management toward sustainability is laid by this combination.

Consider an eco-industrial park where businesses use IS networks to connect with one another and adopt zero waste practices. This results in a self-sustaining ecosystem with constant energy and material flow. According to Geng et al. (2010), these cooperative endeavours are essential for attaining decarbonization, resilience, and resource security in a future where resources are become more limited.

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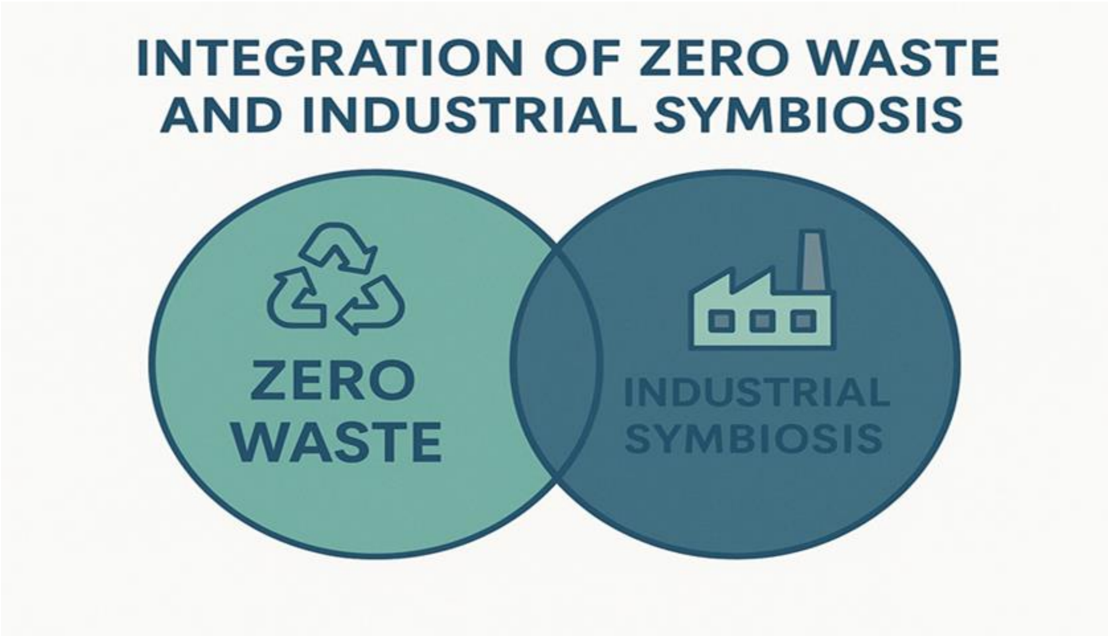

Figure 3: Integration of Zero Waste and Industrial Symbiosis

Conclusion

Zero waste technologies and industrial symbiosis are key components of the circular economy, offering innovative and effective ways to tackle environmental issues, resource shortages, and unsustainable industrial practices. Zero waste technologies aim to cut down on waste right from the start by rethinking processes to boost resource efficiency and lessen environmental harm. This involves approaches like eco-design, sustainable materials management, and better recycling and recovery systems. At the same time, industrial symbiosis encourages collaboration between industries, allowing one company's by-products or waste to become valuable resources for another. This material exchange creates closed-loop systems, transforming potential waste into economic opportunities.

Bringing together zero waste principles with industrial symbiosis sparks a significant shift from traditional linear production models to regenerative, circular systems. These integrated approaches help ease the pressure on landfills, reduce greenhouse gas emissions, and conserve natural resources. Plus, they promote economic sustainability through cost savings and innovation, while also supporting social goals like job creation, community development, and improvements in public health.

To effectively scale and maintain these practices, it's essential to create supportive policies, invest in clean technologies, and involve stakeholders from various sectors. Governments, industries, academia, and civil society all have crucial roles in raising awareness, educating, and implementing these strategies. By encouraging collaboration and a systems-thinking approach, zero waste and industrial symbiosis can be successfully applied across different industrial sectors and regions. Ultimately, embracing these practices is not just a smart move for sustainable industry; it's also a moral obligation to help build a resilient, fair, and low-carbon global economy.

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Zero-Waste Technologies and Industrial Symbiosis: Pathways to Green Chemistry, Driving Circular Economy of Sustainable Technologies, and Achievements

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Abstract

The shift toward zero-waste technologies and industrial symbiosis are key steps for achieving green chemistry, sustainable technologies, and the United Nations Sustainable Development Goals (SDGs). This study examines the principles, mechanisms, and regulatory frameworks of zero-waste and industrial symbiosis, focusing on their role in resource efficiency, waste minimization, and environmental protection. Based on international case studies and new studies, this article examines on how these strategies propel innovation in industrial networks, support circular economy frameworks, and facilitate SDG goals, especially responsible consumption and production (SDG 12), climate action (SDG 13), and clean water (SDG 6). The discussion covers regulatory practices, technological innovations, challenges, and the way forward, and provides recommendations for policymakers and industry leaders.

Keywords: Circular Economy, Resource Efficiency, Waste Minimization, Zero-waste Technologies, Industrial Symbiosis, Green Chemistry, Sustainable Technologies, Environmental Policy, Regulatory Practices, SDGs.

Introduction

As industrialization and urbanization have increased, the rate at which resources get depleted and waste has been generated has accelerated tremendously, endangering the stability of economies as well as the health conditions of the

environment (Ichimura, M. 2003). UNEP 2011 discussed a scarce-resource world with mounting environmental problems that makes traditional linear models such as extraction, utilization, and disposal of resources—in economical manner. Consequently, industrial symbiosis and zero-waste technologies became necessary alternatives for steering industrial systems towards more circularity and sustainability. Kerdlap, P et.al stated that the zero-waste technologies focus on designing products and processes that prevent waste at every stage, emphasizing reuse, recycling, and recovery to minimize reliance on virgin materials and reduce pollution. (Kerdlap, P et.al 2019) On the other hand, Stoyell and coworkers extended the approach beyond end-of-pipe solutions, incorporating eco-design, material substitution, and process improvements to keep materials circulating at their highest value for as long as possible. (Stoyell, J. L. 2004) Industrial symbiosis complements zero-waste efforts by encouraging collaboration between different industries. (Curran, T., & Williams, I. D. 2012) Branca et.al has discussed exchanging by-products, energy, water, and information, industrial symbiosis turns waste from one process into a valuable input for another, improving resource efficiency and reducing environmental impact. This linked way of working forms a key part of the circular economy, which seeks to separate economic progress from the need to constantly use up resources and instead helps restore natural environments. (Branca, T. A. et.al 2021) Bringing zero-waste methods and industrial symbiosis together is now widely seen as a strong force behind the development of greener chemistry and more sustainable technologies. (Chen, T. L. et.al. 2020). This combination help industries move toward circular models that match the aims of the United Nations' Sustainable Development Goals—particularly those focused on responsible consumption, addressing climate change, and ensuring clean water. International initiatives and case studies demonstrate the effectiveness of these strategies in reducing emissions, boosting recycling, and saving water, widespread adoption still faces regulatory, technical, and economic barriers.
Zaman has suggested that by overcoming these obstacles will certainly require coordinated understanding on zero-waste technologies, policy, stakeholder engagement, and supportive infrastructure. Ultimately, zero-waste technologies and industrial symbiosis represent a paradigm shift—i.e., redefining waste as a resource, fostering collaboration, and paving the way for a sustainable, resilient, and inclusive industrial future. (Zaman, A. 2022)

Understanding Zero-Waste Technologies

Definition and Principles

- **Definition**

Zero-waste technologies are specialized systems and processes designed to prevent waste creation in industrial environments by maximizing the reuse, recycling, and recovery of all materials. These approaches move against the conventional linear model of "take-make-dispose" and instead keep resources circulating within the system for as long as possible.

- **Closed-Loop Systems**

The fundamental objective is to create closed-loop industrial systems, whereby the output or by-product of one process is utilized directly as an input for another. In this way, avoidable waste is converted into useful resources with less demand for new raw materials and less environmental pollution. This is mimicking the effective, wasteless cycles that exist in nature.

- **More than Waste Treatment**

Zero-waste technologies are interested in more than treating waste at the end of a process. They are interested in green design, replacement of risky materials with safer ones, and continuous process improvement from the start. This makes products and processes resource-efficient and environmentally sound throughout their lifecycle.

- **Industrial Symbiosis**

These technologies promote collaborations between industries so that the waste or by-products produced by one firm can be used as raw materials by another. Such cross-industry cooperation, known as industrial symbiosis, enhances the efficient use of resources and supports the transition toward more circular and sustainable industrial processes.

- **Sustainability Goals**

Zero-waste technologies play a crucial role in conserving material value, reducing harm to the environment, and fueling innovation. In doing this, they contribute significantly to the achievement of global sustainability goals and to sustainable patterns of production and consumption.

- **Key Strategies**

Several approaches in zero-waste technologies are aimed at changing industrial systems to eliminate waste and increase resource efficiency in all stages of production. (Awasthi, A. K., et.al 2021., Buchert, M. et.al 2019. Li, C. et.al 2023)

Design for Recycling and Reuse (D4R)

This strategy focuses on creating products and processes that can be efficiently disassembled, repaired, refurbished, and recycled in terms of materials. By prioritizing modular design and straightforward assembly, industries can extend product lifespan and facilitate easier recovery of precious materials for reuse.

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Utilizing Digital Tools

The use of digital technologies—like Radiofrequency Identification (RFID) tracking and product lifecycle management-specific software—enables close tracking of materials throughout production. Such solutions enable the detection of inefficiencies, optimize resource flows, and facilitate continuous improvement of how resources are utilized and recovered.

Enhancing Process Efficiency

Another important strategy is improving manufacturing and operations processes. By optimizing these processes, organizations are able to utilize fewer resources, produce less waste, and emit fewer emissions. Adopting best practices in energy and water management and taking action to minimize waste results in a distinct benefit to the environment and business bottom line.

Substituting Materials

Zero-waste methods aim at substituting materials that are dangerous or non-renewable with safer and more renewable materials. This transition reduces risks to the environment and human health, promotes the utilization of renewable resources, and reduces dependence on scarce materials.

Impact in Combination

Overall, these approaches assist industries in keeping material in use for extended periods, reduce their environmental impacts, and advance toward circular, sustainable modes of producing goods.

Functions and core concepts of industrial symbiosis were discussed as follows: (Islam, K., et.al 2016; Shi, X et.al 2013)

Concept and Practice

Industrial symbiosis is where different industries collaborate with each other to exchange by-products, waste products, energy, and water, recycling what one business throws away into valuable resources for another. This web-based strategy converts conventional linear production systems into circular ones.

Major functions

- **Resource Sharing:** Exchange of materials, energy, water, and information between companies.
- **Regional Clusters:** Proximity enables efficient logistics and fosters collaboration.
- **Mutual Benefit:** All participants gain economic and environmental advantages.

Case Study: Kalundborg, Denmark

Enhancing Quantitative Evidence in Zero-Waste and Industrial Symbiosis

While the theoretical advantages of zero-waste technologies and industrial symbiosis are well established, empirical data from real-world applications provide concrete proof for their effectiveness. For example, the Kalundborg industrial symbiosis network in Denmark has achieved a 30% reduction in water consumption among participating companies and has resulted in annual savings of 250,000 tons of CO_2 emissions (Table 1). Similarly, the European Union's ZeroWIN project demonstrated that integrating industrial symbiosis can lead to at least a 30% reduction in greenhouse gas emissions, over 70% reuse and recycling of industrial waste, and a 75% decrease in fresh water usage across project sites.

Table 1: Quantitative Outcomes from Leading Case Studies.

Case Study	GHG Reduction (%)	Water Savings (%)	Waste Reuse/Recycling (%)	Annual CO_2 Savings (tons)
Kalundborg, Denmark	-	30	-	250,000
Zero WIN Project (EU)	≥30	75	>70	-

The strategies approached by Kalundborg Symbiosis (Symbiosis, K 2022) have contributed directly to the United Nations' Sustainable Development Goals (UN SDGs)—particularly;

- **SDG 6 (Clean Water and Sanitation):** Notable reductions in industrial water consumption and pollution.
- **SDG 12 (Responsible Consumption and Production):** Substantial increases in recycling rates and reductions in landfill dependency.
- **SDG 13 (Climate Action):** Significant and measurable decreases in greenhouse gas emissions.

Green Chemistry and Sustainable Technologies

Role in Zero-Waste and Industrial Symbiosis

Integrating Green Chemistry with Zero-Waste Technologies and Industrial Symbiosis, Green chemistry forms the scientific backbone for zero-waste technologies and industrial symbiosis by steering the design of safer materials, processes, and products that reduce environmental and health risks (Kashnitsky, Y et.al. 2024; Kumari, C. et.al. 2025, Chen, T. L. et.al. 2020). Its principles—such as minimizing toxicity, using renewable resources, and preventing waste at the source—are fundamentally aligned with zero-waste objectives.

In zero-waste systems, green chemistry guides eco-design choices, promoting the use of non-hazardous, biodegradable, or recyclable materials. For instance, industries adopting renewable feedstocks and cleaner synthesis techniques like using biocatalysts can produce goods with fewer by-products and less pollution. Future-oriented separation and purification technologies based on green chemistry further facilitate effective recovery of precious materials from waste streams, enabling closed-loop material cycling.

Industrial symbiosis amplifies these gains by making it possible for the sharing of harmless by-products among industries. When businesses incorporate green chemistry, their products—like non-toxic solvents or biodegradable intermediates—become safer and more useful inputs for other plants, minimizing risks of contamination and simplifying product exchanges. For instance, the utilization of green solvents in one factory can enable another to directly use these materials, without the necessity for extensive processing.

Real-world projects such as the Zero WIN initiative and eco-industrial complexes like Kalundborg demonstrate how the synergy between green chemistry with zero-waste and industrial symbiosis approaches can bring meaningful greenhouse gas emissions reductions, promote material reuse, and conserve water. Such outcomes contribute to both environmental sustainability and economic growth in industrial clusters.

Integrating green chemistry principles at the centre of zero-waste and industrial symbiosis ensures that development for circularity is both efficient and safe, serving directly to support global sustainability targets and the United Nations Sustainable Development Goals.

Technological Innovations of Bio catalysis and Enzyme Technology Enabled selective transformations with minimal waste. It also involves advanced separation processes which facilitate the recovery and purification of valuable materials from waste streams and renewable Feedstocks where the process involves the use of biomass and other renewable resources as raw materials. (Browne, R C. (2015)

Regulatory systems intended to advance zero-waste technologies and industrial symbiosis vary significantly in terms of design and efficacy across the globe. The European Union leads the way with overarching policies like the Circular Economy Action Plan and Waste Framework Directive, which have resulted in higher recycling rates and the emergence of eco-industrial parks. The United States' Resource Conservation and Recovery Act (RCRA) focuses on waste reduction but provides less direct support for industrial symbiosis. In Asia-Pacific, countries such as Japan and South Korea have experienced success through eco-town and policy of resource circulation, but outcomes depend on enforcement and industry buy-in. Despite these systems, enforcement problems still persist globally, such as regulatory sophistication, overlapping regulators, and patchy monitoring, which can hinder compliance and limit policy effectiveness. The effectiveness of such regulations is to a great extent dependent on local infrastructure, government, and secondary material quality standards, which vary considerably. To enhance outcomes, harmonization of standards, stronger enforcement with improved monitoring and online aids, selective incentives, stakeholder capacity building, and promotion of international cooperation to align policies and develop global secondary material markets are advised. This more in-depth analysis underscores the requirement for finely tailored, well-enforced, and coordinated policy mechanisms to achieve the best possible benefits of zero-waste and industrial symbiosis programs. (Branca, T A. et.al. 2024; Grasso, D. 2017)

International and Regional Policies

- **European Union:** The EU Circular Economy Action Plan and Waste Framework Directive set ambitious targets for waste reduction, recycling, and resource efficiency, encouraging industrial symbiosis and zero-waste practices (Clift, R., & Druckman, A. 2015).
- **United States:** The Resource Conservation and Recovery Act (RCRA) promotes waste minimization and sustainable materials management by Branca, T. A. et.al. 2024.
- **Asia-Pacific:** Countries like Japan and South Korea have implemented eco-town and resource circulation policies to foster industrial symbiosis (Mazur-Wierzbicka, E. 2021).

Key Regulatory Mechanisms

- **Extended Producer Responsibility (EPR):** Mandates that producers are responsible for the end-of-life management of their products, incentivizing design for recyclability and reuse (Van Berkel, R et.al 2009).
- **Eco-Design Standards:** Require products to meet criteria for durability, reparability, and material recovery (Tojo, N. et.al. 2001).
- **Incentives and Subsidies:** Financial support for companies adopting zero-waste technologies or participating in industrial symbiosis networks (Tojo, N. et.al. 2001).
- **Reporting and Monitoring:** Mandatory disclosure of material flows, waste generation, and recycling rate (Tojo, N. et.al. 2001).

Zero-Waste, Industrial Symbiosis, and the SDGs

Alignment with SDG Goals (Bocken, N. M et.al 2016)

- **SDG 6: Clean Water and Sanitation**

Industrial symbiosis networks frequently incorporate water recycling and reuse, which helps decrease the need for fresh water and limits water pollution.

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- **SDG 9: Industry, Innovation, and Infrastructure**

These practices encourage the development of robust infrastructure and drive innovation within sustainable industrial sectors.

- **SDG 12: Responsible Consumption and Production**

By enhancing resource efficiency and minimizing waste, zero-waste strategies and industrial symbiosis play a direct role in promoting sustainable production and consumption habits.

- **SDG 13: Climate Action**

Through improved efficiency in energy and materials, these methods help reduce greenhouse gas emissions, thereby supporting efforts to combat climate change.
The strategies and best practices for the implementation for industrial symbiosis are discussed as follows: (Baldassarre, B. et.al. 2017; Jacobsen, N. B. 2006; Chertow, M. R. 2000; Fraccascia, L. et.al. 2019)

Building Industrial Symbiosis Networks

Mapping Resource Flows

Creating industrial symbiosis starts with mapping systematically how materials and energy flow through and across industries. The mapping identifies opportunities where the waste or by-product of one facility can be used as an input for another, making resources more efficient and less wasteful.

Stakeholder Engagement

Close interaction between businesses, local governments, and research organizations is crucial. Transparency and trust can facilitate collaborative resource sharing, best practice sharing, and joint problem-solving, all of which contribute to innovation and sustainable development.

Digital Platforms

Electronic resource exchange sites facilitate supply matching with demand for secondary and by-products more easily. The online platforms enhance transparency, simplify transactions, and enable industries to locate new collaboration opportunities, increasing resource sharing to be more efficient and scalable.

Capacity Building

Ongoing education and knowledge-sharing are crucial to build expertise in zero-waste and symbiotic practices. Workshops, seminars, and collaborative research projects keep stakeholders informed on technological developments, regulatory changes, and new best practices, leading to continuous improvement and wider uptake.
The technology integration involved in industrial symbiosis includes the

following (Krom, P. et.al. 2022; Tao, F. et.al. 2018; Assessment, L. C. 2022)

Automation and IoT
The use of automation and Internet of Things (IoT) solutions provides for ongoing monitoring and management of resource consumption. Through sensors and automated controls, organizations are able to track materials, energy consumption, and waste production in real time, allowing them to detect inefficiency immediately and adjust accordingly for maximum performance.

Life Cycle Assessment (LCA)
LCA provides an overall assessment of the environmental effects of processes and products. It informs decision-making through the identification of where improvement must come, enabling more environmentally friendly materials and technology to be chosen, and enabling zero-waste programs to contribute effectively in the environment.

Modular Design
Modular product design makes it easier to disassemble, repair, and recycle toward the end of their life. This promotes circularity through the ability to reuse or recycle components seamlessly, lessening the pressures on virgin resources and reducing waste.

1. **Opportunities and Benefits**

The coupling of zero-waste innovations and industrial symbiosis presents a wide range of opportunities for governments, industries, and society as a whole. (Grasso, D. 2017; Jacobsen, N. B. 2006; Yang, M. et.al. 2018; Shi, X., & Li, X. 2019.) These strategies promote a fundamental move away from the old linear "take-make-dispose" approach to a circular economy, with resources engineered to remain in use for as long as possible, generating maximum value and minimum waste.

- **Economic Benefits**

Industries which adopt symbiotic and zero-waste practices are likely to save significant amounts of money through reduced raw material usage, lower waste disposal, and process efficiency. As waste streams are converted into valuable resources, companies can generate new revenue streams and enable product and process design innovations. The establishment of industrial symbiosis networks, for example, eco-industrial parks, also promotes regional economic growth, investment attraction, and green employment.

- **Environmental Impact**

Zero-waste technologies and industrial symbiosis directly lead to greenhouse gas emission reduction, water and energy conservation, and pollution reduction of land and water. Closing material loops through these practices reduces virgin resource extractions needed, hence preserving biodiversity and ecosystem functions. The application of green chemistry principles also helps ensure that the materials and processes used are less harmful to human health and the environment.

- **Social and Policy Implications**

These strategies promote a greener, more resilient and equitable society. They encourage cross-industry collaboration, urban government, research centers, and communities, creating trust and mutual accountability for sustainable stewardship of the environment.

2. Barriers and Challenges

Even with their evident advantages, the general implementation of zero-waste technologies and industrial symbiosis are complicated by a number of serious challenges. (Tseng, M. L., et.al. 2018; Wang, F., et.al. 2019)

- **Regulatory and Policy Barriers**

Regulatory regimes for waste management and resource recovery are frequently patchy and incoherent within regions. In other instances, old laws might even treat some by-products as waste, limiting their reuse and trading. Standardizing requirements, legally defining the terms, and issuing facilitative policy frameworks are necessary to enable industrial symbiosis.

- **Technical and Logistical Issues**

Zero-waste and symbiotic solutions involve sophisticated technological capacities, including real-time sensing, process optimization, and material tracking. Maintaining the quality and compatibility of secondary materials can be challenging, particularly when combining heterogeneous industrial processes. Logistics, including transporting and storing by-products, are also problematic, mainly for SMEs.

- **Economic and Market Constraints**

Seed investments in new technology, infrastructure, and employee training can be high. Economically viable industrial symbiosis usually hinges on production scale and market stability for secondary materials. Unpredictable commodity prices and uncertain recycled product demand can erode the business case for zero-waste operations.

- **Cultural and Organizational Factors**

Resistance to change, unawareness, and sparse expertise can hamper the practice of novel practices. Establishment of a culture of trust and cooperation between industries is essential for effective symbiosis but may prove challenging, particularly in competitive economies.

3. Future Directions and Recommendations

A multi-faceted approach is required to unlock the full potential of zero-waste technologies and industrial symbiosis, which includes Policy and Regulatory Reform: Governments should streamline regulations, incentivize resource sharing, and support the development of eco-industrial parks. Extended producer responsibility (EPR), eco-design standards, and green public procurement can further drive adoption.

- **Technological Innovation:** Investment in research and development of green chemistry, advanced recycling, and digital platforms for resource exchange is essential. Life cycle assessment (LCA) tools should be integrated into decision-making processes to quantify benefits and guide improvements.
- **Capacity Building and Education:** Training programs, knowledge-sharing platforms, and demonstration projects can build expertise and showcase successful models.
- **Stakeholder Engagement:** Industry, academia, government, and civil society collaboration is essential. Clear communication and common objectives can bridge over obstacles to trust and collaboration.
- **Global Collaboration:** Cross-country and cross-region sharing of best practices and lessons learnt can hasten advances and ensure solutions are flexible across contexts.

Conclusion

Zero-waste technologies and industrial symbiosis lead the way toward a sustainable industrial system. Recasting waste as a resource and promoting collaborative networks between industries, offer a viable pathway to achieve the goals of green chemistry, sustainable technologies, and the UN SDGs. The advantages are obvious: lower environmental footprint, improved resource utilization, cost savings, and new business opportunities. Nonetheless, if zero waste and industrial symbiosis are to live up to their full potential, major hurdles still exist in relation to regulation, technology, money, and cultural mentality. Policymakers need to create simple, encouraging frameworks to foster innovation and resource sharing. Companies should invest in new technologies and adopt the mindset of teamwork and continuous improvement. It is also important to educate and train the people so that everyone has the knowledge and capabilities to implement these solutions and further develop them. The intersection of zero-waste technologies and industrial symbiosis will be the secret for building robust, low-carbon, and circular economies in the future. Such actions not only address pressing environmental concerns but also create value for businesses and society. Zero waste and industrial symbiosis will remain central pillars for global sustainability endeavors as the world strives to meet the SDGs and a sustainable future.

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Precision and Sustainable Agriculture

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Abstract

Precision Agriculture (PA) is transforming traditional agricultural practices by leveraging advanced technologies to monitor and manage in-field spatial variability. It utilizes diagnostic tools such as yield monitors, near-infrared reflectance sensors, geographic information systems (GIS), and remote sensing to collect and analyze data on soil and crop conditions. This data-driven approach enables farmers to make informed, site-specific management decisions.

By employing variable rate application technologies integrated into farm machinery, PA facilitates spatially and temporally differentiated treatments. These tools allow visualization and targeted intervention based on fluctuations in production resources. The core driver of PA adoption is the recognition of within-field variability and the opportunity to treat different areas of a field or production unit uniquely.

PA supports a wide range of cultural practices, including precision tillage, seeding, fertilization, irrigation, and pesticide application. It also informs strategic decisions such as site-specific deep tillage to alleviate soil compaction. By optimizing input use, PA enhances farm profitability and promotes environmental stewardship.

Overall, PA plays a vital role in sustainable soil and crop management by reducing the overuse of inputs, increasing efficiency, and contributing to environmentally responsible agriculture.

Keywords: Precision agriculture, GIS, Remote sensing, Tillage, Variable rate fertiliser application

Introduction

Soil and water are essential natural resources for food production and human survival. However, increasing urbanization and the adverse effects of climate change are placing tremendous pressure on these vital resources. As global populations rise and living standards improve, the demand for food continues to escalate. Feeding an estimated 9 billion people by 2050, despite limited arable land and finite natural resources, presents an urgent challenge.

Precision Agriculture (PA) has emerged as a promising technological solution to enhance global agricultural productivity in a sustainable manner. Often described as “the science of improving crop yields and supporting management decisions using high-tech sensors and analytical tools,” PA blends scientific principles with technological innovations to optimize farm inputs and outputs. By integrating tools such as Geographic Information Systems (GIS), remote sensing, spatial statistics, and Farm Management Information Systems (FMIS), PA aims to improve productivity, profitability, and resource efficiency while minimizing environmental impact.

Furthermore, when combined with genetic advances in crop breeding, PA holds the potential to meet global demands for food, feed, fiber, and fuel. PA promotes the site-specific management of agricultural inputs—fertilizers, water, pesticides, and seeds—within fields to maximize yield and preserve environmental quality. Rapid advances in onboard computing power have accelerated the development and deployment of PA technologies, incorporating tools like GNSS, geo-mapping, robotics, and sophisticated data analysis.

A wide range of sensing technologies—including in-situ sensors, spectroradiometers, machine vision, multispectral and hyperspectral imaging, thermal sensors, and satellite photography—are used by researchers and progressive farmers to monitor crop health and field conditions. These tools provide essential data for **Site-Specific Management (SSM)** of crop biomass, nutrient status, weed presence, and soil characteristics.

Modern agricultural equipment, equipped with advanced capabilities for precise data collection and control, is transforming PA by capturing high-resolution field data and supporting real-time decision-making. Systems that combine GNSS and GIS allow for navigation control, path planning, map displays, sensor system integration, and data exchange. For example, GNSS-guided auto-steering tractors optimize path planning, reduce overlaps, and improve operational efficiency.

Map-driven seeding technologies allow for the alignment of plant populations and genetics with specific soil landscapes, using yield monitor data from previous seasons. This data can also guide nutrient and irrigation management strategies, enhancing both productivity and profitability. The concept of **"Smart Irrigation",** an application of the Internet of Things (IoT), has also gained prominence in precision agriculture. These systems monitor soil moisture levels and manage irrigation schedules in real-time while maintaining detailed records of field conditions and water usage.

Beyond enhancing the efficiency of large-scale farming, PA technologies can significantly reduce input costs. For example, research conducted in the UK has demonstrated that **Variable Rate Technology (VRT)** for nitrogen management led to yield improvements across 20–30% of a 250-hectare farm, with productivity gains of 0.25 to 1.10 Mg/ha. Similarly, a three-year study by Longchamps and Khosla showed that VRT not only improved nitrogen use efficiency but also minimized environmental nitrogen loading without sacrificing yields.

Compared to traditional practices, PA reduces overall production costs while maintaining or improving yields. Its adoption is influenced by numerous factors such as topography, soil properties, nutrient levels, crop canopy, water availability, rainfall distribution, pest and disease pressure, and cropping systems. While some factors like soil pH, phosphorus (P), and potassium (K) exhibit low variability and are easily managed, others—such as pest and disease outbreaks—require more responsive strategies. Effective PA depends on understanding and managing both the **spatial and temporal variability** in agricultural production systems through methods like field scouting, soil sampling, yield monitoring, and remote sensing.

Fig 1: Precision Agriculture for Sustainability

Enhancing the sustainability of agriculture requires the adoption of practices that ensure the responsible management of soil and crops. Among the prominent strategies under consideration by researchers are precision farming, sustainable intensification, climate-smart agriculture, and integrated soil management. These approaches collectively aim to align productivity with environmental stewardship. The implementation of Best Management Practices (BMPs) across agroecosystems is essential to this effort, as they:

i) ensure the optimal utilization of natural resources,

ii) preserve and enhance soil health and quality, and

iii) safeguard current environmental and societal benefits without compromising the prospects of future generations.

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Numerous studies affirm that the integration of Precision Agriculture (PA) technologies can significantly contribute to these goals. PA facilitates the efficient use of inputs, thereby reducing variable costs, enhancing farm productivity, and increasing profitability. Simultaneously, it mitigates the negative environmental impacts associated with conventional agricultural practices. By leveraging data-driven tools and site-specific management techniques, PA supports the transition toward more resilient, productive, and sustainable agricultural systems.

Precision Agriculture

Precision Agriculture (PA) is an advanced and innovative farming approach enabled by the measurement of crop production variables and the application of information technology (IT). Over the years, researchers have coined various terms to describe the implementation of PA techniques in modern agriculture. These *include precision farming, site-specific farming, site-specific management, spatially variable crop production, grid farming, technology-based agriculture, smart farming, and satellite farming, among others.*

The **National Research Council** defines PA as "a management strategy that uses information technologies to bring data from multiple sources to bear on decisions associated with crop production." Expanding on this, Olson provided a more comprehensive definition, describing PA as "the application of a holistic management strategy that uses information technology (IT) to bring data from multiple sources to bear on decisions associated with agricultural production, marketing, finance, and personnel."

In simpler terms, PA leverages **Geographic Information Systems (GIS)** to map and manage in-field variability, aiming to optimize farm output by ensuring the most efficient use of inputs. It integrates **GIS and Global Navigation Satellite Systems (GNSS)** to deliver precise, location-based data on crop health and soil variability. Through the coordinated use of sensors, IT tools, automated machinery, and informed decision-making, PA addresses the inherent unpredictability and complexity of agricultural systems.

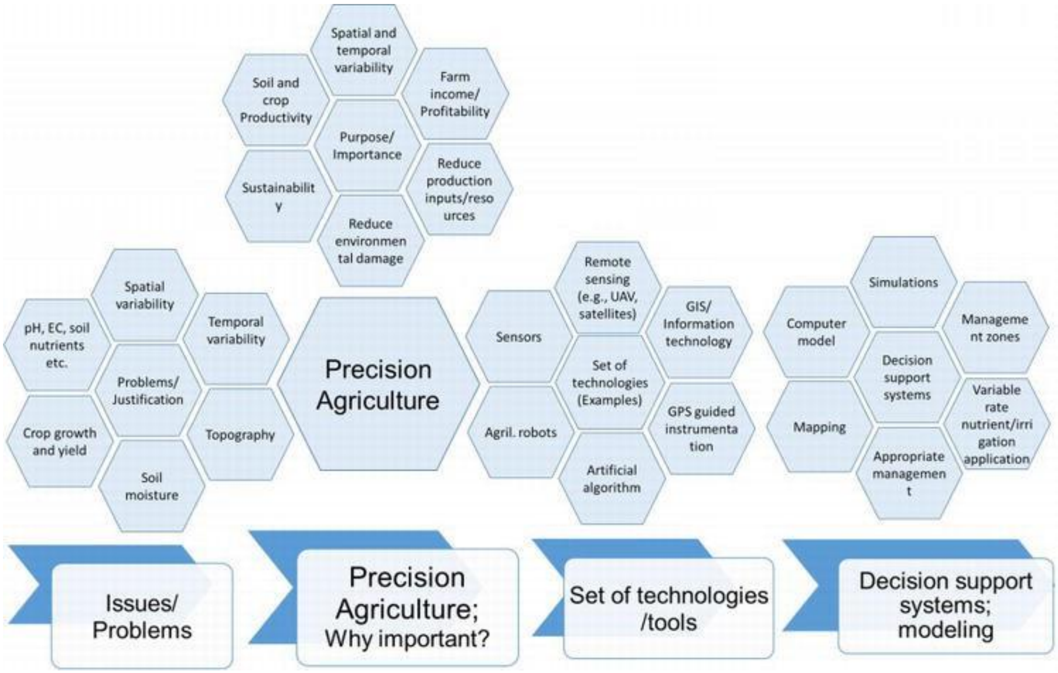
The overarching aim of Precision Agriculture is to enhance sustainable soil and crop management by maximizing resource efficiency. This is intended to increase food production, improve long-term farm profitability, and minimize environmental degradation. Specifically, the goals of PA include:

1. Increasing farm profitability
2. Enhancing agricultural productivity
3. Reducing unnecessary investments and input costs
4. Minimizing soil erosion
5. Reducing the environmental impact of fertilizers and pesticides

6. Facilitating the sustainable management of large-scale farms

Overall, Precision Agriculture represents a paradigm shift in farming practices, combining technology and sustainability to meet the growing global demand for food while conserving natural resources.

Fig 2: A brief diagram of precision agriculture indicates concerns due to spatial and temporal variability, possible solutions/importance of PA, and a set of technologies encompassing PA and decision support systems



Importance of Precision Agriculture (PA)

Precision Agriculture (PA) is a modern farm management technique that utilizes information technology (IT) to enhance agricultural productivity, operational efficiency, and profitability. By optimizing land use, minimizing input costs, and refining crop management practices, PA contributes to increased crop yields and improved crop health. The integration of technological innovations—such as **Global Navigation Satellite System (GNSS) guidance, autonomous tractors, agricultural drones, Geographic Information Systems (GIS), sensors**, and specialized software—is revolutionizing farming practices. These technologies empower farmers to determine the precise types, amounts, and placement of inputs required to achieve optimal crop performance while conserving resources.

PA ensures precise control over various field operations essential to crop production. This data-driven, site-specific approach supports the long-term sustainability of agriculture by promoting **eco-friendly input management** strategies. A fundamental requirement of PA is the farmer's understanding of **within-field variability**, a concept often overlooked in traditional farming systems.

In conventional agriculture, inputs such as fertilizers and pesticides are frequently applied uniformly across entire fields. This uniform application disregards the natural variability in soil characteristics—such as **texture, electrical conductivity, moisture levels, pH, and nutrient availability**—as well as topographical features and historical management practices like crop rotation, compaction patterns, and fertility planning. As a result, a portion of these blanket-applied inputs remains unused by crops, leading to **increased production costs and environmental degradation** due to runoff and pollution.

Research, including studies conducted in the **United Kingdom**, has shown significant variability in crop yield patterns and magnitudes, even in uniformly managed fields. These disparities are attributed to soil heterogeneity, inconsistent rainfall distribution, and varying field activities. To address these challenges, PA introduces the concept of **Site-Specific Management Zones (SSMZs)**, which divide a field into sub-zones with customized treatment plans based on spatial variability.

This targeted input management approach not only improves **nutrient-use efficiency**, particularly for environmentally sensitive macro- and micronutrients such as **nitrogen (N)**, but also enhances overall farm productivity and profitability. Consequently, PA plays a pivotal role in achieving both economic and environmental sustainability in modern agriculture.

Using Precision Agriculture (PA) for Sustainable Crop and Soil Management

In contemporary agriculture, **efficiency, economic viability, and environmental sustainability** are the primary driving forces—objectives that are closely aligned with the principles of **Precision Agriculture (PA)**. PA offers a suite of technologies and strategies that support the selection and implementation of **Best Management Practices (BMPs)** for sustainable crop production within diverse agricultural settings.

Through the integration of **technological expertise** and data-driven decision-making, PA enables the adoption of **sustainable soil and crop management practices**. It empowers farmers with tools to better understand spatial and temporal variability within their fields, leading to more informed and environmentally conscious farming decisions.

Key components of PA that contribute to sustainable management include:

- **Soil sampling** and **geostatistical analysis** for understanding soil variability
- **Geographic Information Systems (GIS)** and **Global Positioning Systems (GPS)** for spatial mapping and site-specific planning

- **Site-specific farming** and **management zones** for localized input application
- **Yield mapping** to assess productivity and performance over time
- **Variable-rate application** of nutrients, herbicides, and irrigation for resource efficiency
- **Remote sensing** and **proximal sensing technologies** for real-time monitoring of soil and crop health
- **Automatic tractor navigation, robotics**, and mechanized precision tools for accurate and efficient field operations

These technologies not only enhance **input-use efficiency** and **crop productivity**, but also reduce **environmental degradation** by minimizing over-application of chemicals and conserving water and energy. Moreover, PA contributes to long-term **soil health** and supports the **economic viability** of farming operations by lowering production costs and increasing profitability.

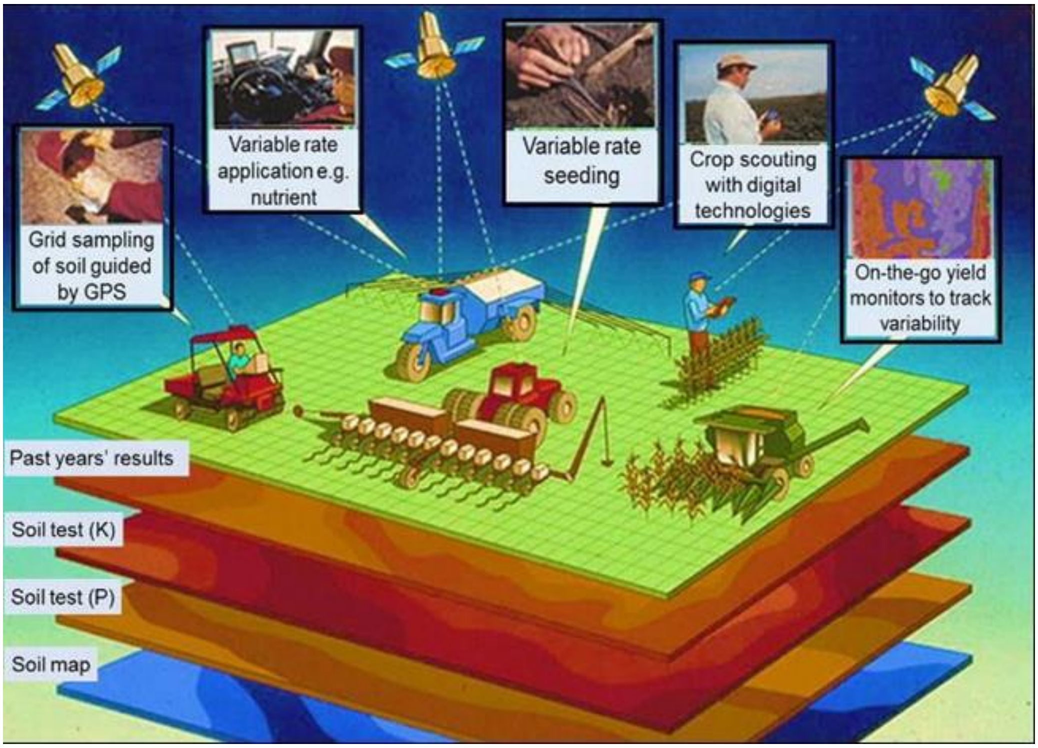


Fig 3: Precision farming illustration: High-tech tools for site-specific crop management

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Applications of Geospatial Data in Agriculture

Geospatial technologies encompass a range of tools and methods used to collect, map, and analyze data related to the Earth's surface and human activity. These technologies include **Remote Sensing (RS), Geographic Information Systems (GIS), Global Navigation Satellite Systems (GNSS),** and **internet-based mapping tools** such as Google Earth and Microsoft Virtual Earth.

Geospatial data—also known as **geo-referenced data**—can be integrated with other spatial datasets to produce layered digital maps representing specific locations on the Earth's surface. These layers enable detailed analysis and visualization, which are critical for informed decision-making in **modern, technology-driven agriculture**.

In Precision Agriculture, **automated field machinery** is essential for executing field operations with high accuracy. Guided by GIS and GNSS, such machines follow pre-defined optimal paths based on real-time positional data, allowing for **precise input application** and **resource-efficient management**. However, the effectiveness of geospatial technology hinges on the **accuracy, quality, and interpretation** of the data collected.

Key Applications of Geospatial Data in Precision Agriculture

1. **Mapping and Monitoring**
   - **Remote sensing** provides high-resolution images (≤1 meter) that monitor crop conditions, detect stress, and assess field variability.
   - Satellite and drone-based imagery support real-time surveillance of crop health and soil characteristics.
2. **Creation of Management Zones**
   - Large agricultural fields are subdivided into Site-Specific **Management Zones (SSMZs)** based on geospatial analysis.
   - Each zone reflects specific crop needs and environmental constraints, enabling targeted input applications.
3. **Data Integration and Analysis**
   - **GIS software** processes and converts data into digital maps using techniques like **kriging** for spatial interpolation.
   - A GIS database stores geo-referenced data, linking field observations from sensors and remote sensing to precise coordinates.
4. **Crop and Soil Characterization**
   - Management zone delineation depends on:
   - o **Crop attributes:** canopy cover, plant density, pest and disease presence, nutrient needs, hybrid responses, and stress indicators.
   - o **Soil properties:** texture, pH, electrical conductivity (EC), moisture content (MC), compaction, and nutrient availability.

- o **Weather data and forecasts**, which influence growth cycles and input timing.

5. **Productivity Assessment and Forecasting**
   - Remote sensing data is used to estimate indicators such as **chlorophyll content**, which correlate with plant health, yield potential, and productivity.
   - These indicators are spatially analyzed using GIS to inform decisions on irrigation, fertilization, and pest control.
6. **Visualization and Communication**
   - Platforms like **Google Earth** and **Microsoft Virtual Earth** revolutionize how geospatial data is viewed, analyzed, and shared among stakeholders.

Remote Sensing in Precision Agriculture

Remote Sensing (RS) involves the acquisition of image data from **airborne** or **spaceborne sensors** mounted on platforms such as satellites, aircraft, and **unmanned aerial vehicles (UAVs)**. These technologies have become increasingly prominent in agriculture, offering non-invasive, large-scale methods to monitor and assess soil and crop conditions.

By integrating **georeferenced field data** (e.g., crop and soil properties) with **spectral signatures** collected by sensors, RS can accurately estimate and quantify various **soil attributes** such as moisture, fertility, compaction, and temperature. This approach complements or even replaces traditional field-based methods with a **faster, more cost-effective, and scalable solution**.

Khanal et al. demonstrated that combining remote sensing data with **machine learning algorithms** enhances spatial prediction capabilities for soil parameters and maize yield. This integration not only improves data coverage but also provides high-resolution temporal insights, surpassing conventional soil analysis methods.

Drones (UAVs), both airborne and ground-based, are now being used for a variety of agricultural functions, including:

- **Soil and field analysis**
- **Precision crop planting**
- **Variable-rate pesticide application**
- **Crop growth monitoring**
- **Irrigation scheduling**
- **Crop health diagnostics**

For example, a recent startup introduced a **UAV-based seeding system** that reduces costs by up to 85% compared to traditional methods. Modern sensors can collect detailed agronomic data, such as:

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- **Soil moisture and temperature**
- **Nutrient levels**
- **Leaf area index (LAI)**
- **Leaf surface temperature**
- **Pest and disease infestations**

These datasets are crucial for making informed, site-specific decisions that enhance productivity and sustainability.

Site-Specific Soil and Crop Management

Site-Specific Crop Management (SSCM) is an information-intensive and technology-enabled agricultural practice focused on identifying, analyzing, and managing **spatial and temporal variability** in soil and crop conditions within a field. According to Robert et al., SSCM aims to optimize **profitability, sustainability, and environmental stewardship**.

The foundation of SSCM lies in the development of **Site-Specific Management Zones (SSMZs)** or sub-zones. These zones:

- Are **spatially homogeneous**
- Share **common yield-limiting factors**
- Exhibit similar **productive potential**

Khosla and Alley demonstrated how homogeneous management zones within large fields can improve soil sampling accuracy and resource use efficiency.
Fleming et al. developed nutrient application maps based on these zones to support **Variable Rate Technology (VRT)** applications of fertilizers.

The delineation of spatial variability is primarily based on:

- Soil texture and structure
- pH and electrical conductivity
- Moisture content and nutrient availability
- Crop performance data and weather information

Recent studies suggest that the **optimal grid resolution** for defining management zones in medium- to small-scale farms is approximately **50 meters**.

Furthermore, the adoption of **site-specific deep tillage, tire inflation pressure control systems**, and **controlled traffic farming (CTF)** has proven effective in minimizing soil compaction and enhancing long-term productivity. For instance, **Wells et al.** found that precision tillage at varied depths increased crop yield in one out of three study locations.

Remote sensing and PA technologies are also being used to:

- Measure and map soil compaction
- Model compaction effects
- Implement remedial management strategies

In the **United States**, surveys indicate:

- **40%** of croplands now use **grid sampling** for site-specific lime and fertilizer application
- **GNSS-assisted yield monitors** are used by **43%** for lime and **59%** for fertilizer application

In the **United Kingdom**, studies confirm that autonomous equipment for precision agriculture is **both technically and economically viable**, with the potential to significantly **reduce operational costs**.

This modern integration of **remote sensing** and **site-specific management** represents a transformative shift in how farms can achieve **sustainable intensification**, balancing productivity with environmental care.

Variable-Rate Technology (VRT) in Precision Agriculture

While **Precision Agriculture (PA)** is often perceived as a highly advanced, technology-intensive practice applicable mainly in developed countries, its principles and tools—such as **Variable-Rate Technology (VRT)**—have shown considerable success even in less developed regions. For instance, **micro-dosing** of fertilizers on nutrient-deficient soils in parts of Africa has significantly improved grain yields. Similarly, in **China**, multiple case studies have highlighted the benefits of managing **in-field variability** to enhance productivity and resource efficiency.

A fundamental component of PA involves understanding the **spatial variability of soil properties** within a field. **Geostatistical techniques** are commonly used to assess the distribution of soil characteristics. This spatial insight allows for the creation of **Site-Specific Management (SSM)** strategies that support **sustainable soil and crop productivity**, reduce costs, and minimize environmental impact.

Importance of VRT in Soil Nutrient Management

Site-Specific Nutrient Management (SSNM)—a key feature of PA—relies heavily on VRT to address in-field **spatial and temporal variability** in soil nutrients. Sustainable nutrient management practices, when informed by detailed spatial data, can help prevent **soil degradation** and **optimize crop yields**.

Soil properties such as **moisture content, organic matter, texture**, and **pH** often vary significantly across a single field and are influenced by historical **irrigation**, **tillage**, and **fertilization practices**. VRT enables farmers to tailor **input application rates** (fertilizers, seeds, pesticides, irrigation) according to these

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variations, thereby ensuring that each zone within the field receives the appropriate treatment.

Nitrogen Management and Efficiency Gains

Among all nutrients, **Nitrogen (N)** is the most **mobile and dynamic**, and is vital for crop development and profitability. However, its application must be managed precisely, as it is prone to losses through leaching, volatilization, and denitrification—especially in heterogeneous soils.

Remote sensing and **GIS tools** help in identifying and mapping the landscape-level variability that affects N dynamics. Studies have demonstrated that **VRT-based nitrogen management** can significantly improve **Nitrogen Use Efficiency (NUE)** by aligning application rates with actual crop requirements.

For example, compared to uniform application methods, **site-specific P (Phosphorus) and K (Potassium) management** using VRT has been shown to save approximately **21 kg/ha of P and 30 kg/ha of K**, without compromising crop yield.

Core Advantage of VRT: The Right Input at the Right Place and Time

The primary advantage of PA—especially when implemented with VRT—is the **precise administration of the right input, at the right rate, in the right location.** This leads to:

- Enhanced **crop productivity**
- Increased **input-use efficiency**
- Lower **environmental footprint**
- Improved **economic returns** for farmers

Monitoring and Mapping of Yield in Precision Agriculture

One of the most transformative advancements in **grain production** is the integration of **yield monitors** into modern **combine harvesters**, now commonly provided as standard equipment. These instruments serve as **powerful tools** for farmers to evaluate how various factors—such as **weather conditions**, **soil properties**, and **agronomic management practices**—influence grain yield across fields.

Key Benefits of Yield Monitors

According to **Shearer et al.**, yield monitors provide three main advantages:

1. **Data Collection and Summary**

Yield data can be collected in real time and later transferred to a computer for field-by-field or farm-wide analysis, facilitating detailed record-keeping and strategic planning.

2. **Real-Time Crop Performance Monitoring**

Operators can monitor **crop performance instantly** during harvest, enabling adaptive decisions and quality control throughout the process.

3. Yield Map Generation

The collected data can be used to produce **geo-referenced yield maps**, which visually depict high- and low-yielding zones within a field, allowing comparison across multiple growing seasons.

Yield Mapping: A Foundation of Precision Agriculture

Yield maps are central to the management of **arable farming** in PA. These maps offer insights into spatial variability in crop performance and guide site-specific interventions. Yield mapping is typically one of the **initial steps** in implementing a precision farming system, often accompanied by **soil sampling and lab analysis** to understand soil health in detail.

Requirements for Accurate Yield Mapping

To ensure reliable yield data, the **proper installation, calibration, and operation** of yield monitoring equipment are critical. Inaccuracies at any stage may distort the mapping output and mislead management decisions.

Interpolation Techniques for Yield Mapping

The creation of yield maps from discrete data points involves **spatial interpolation techniques** that estimate yield values for unsampled locations based on nearby known values. Common interpolation methods used in PA include:

- **Inverse Distance Weighting (IDW)**

Values are estimated by averaging nearby points, with **closer points given more weight.**

- **Inverse Square Distance (ISD)**

Similar to IDW but gives exponentially more weight to nearby points.

- **Kriging**

A geostatistical technique that not only considers distance but also **spatial autocorrelation** and trends in the data, often providing more accurate and statistically reliable results.

Integration with Soil Data and Management Practices

While yield monitors reveal the **spatial variability in crop output**, **soil sampling and analysis** offer complementary information on nutrient levels, pH, moisture content, and other soil health indicators. By overlaying **yield maps** with **soil maps** using **GIS tools**, farmers can make more informed decisions regarding:

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- Variable-rate fertilization
- Irrigation scheduling
- Site-specific tillage and planting
- Long-term land-use planning
- Robotics and Emerging Technologies in Precision Agriculture
- Robotics has brought about a radical transformation in agriculture, forestry, and horticulture, with ongoing developments enhancing precision agriculture (PA). The integration of autonomous and robotic technologies is essential for refining crop management practices down to the individual plant level. Technologies such as autonomous tractors, drones, crop-harvesting robots, seeding machines, and robotic weeders are revolutionizing modern farming. These autonomous platforms offer advantages over traditional machinery, from crop harvesting to field preparation, by reducing the environmental footprint of agriculture through precise pesticide and fertilizer application, lower energy consumption, and minimized soil compaction due to lighter machinery. In the Midwestern United States, the agricultural sector is increasingly optimistic about robotic applications in weeding, scouting, and input application using UAVs/drones.

Future Trends and Challenges in Precision Agriculture

However, the future development and implementation of PA practices face several challenges. Adopting PA requires not only new technological skills and knowledge but also a change in mindset among farmers and end users, who are often more comfortable with conventional practices. According to Hightower, overcoming these mental barriers is difficult, and PA adoption is often hindered by high costs, unclear perceived benefits, and the need for specific expertise. Agricultural experts on the front lines may not fully recognize or address these adoption barriers. To enable widespread deployment of PA, the timely collection of low-cost, high-quality soil and yield data is crucial. While autonomous farming equipment offers considerable benefits and has the potential to revolutionize agriculture, its adoption remains limited until it becomes more economically attractive to farmers. In many developing countries, PA is still seen as a conceptual innovation rather than a practical solution. Therefore, strong collaboration between the public and private sectors is essential to accelerate adoption.

Integration of Digital Technologies in PA

Access to reliable data is a cornerstone of PA, but reducing the time between data acquisition and its application in decision-making is equally important. Beyond crop production, PA technologies are gaining popularity in areas like precision grassland management, pasture and range management, and tree management.

The agricultural sector has increasingly embraced advanced technologies from other fields, such as the Internet of Things (IoT), artificial intelligence (AI), and cloud computing. IoT enables various devices equipped with sensors, software, and processing capabilities to communicate autonomously over networks. In agriculture, IoT has been successfully applied in greenhouses and other precision farming systems, allowing farmers to monitor and manage operations remotely, automate labor-intensive tasks, and save time. Smart UAVs, when combined with IoT and cloud computing, further support the development of sustainable smart agriculture.

Data Privacy, Ownership, and Strategic Implementation

Given the financial and operational significance of PA data, privacy and security issues have become critical. It is essential to establish clear ownership and accountability over data and insights, ensuring that stakeholders responsible for generating value from this information are actively involved. Clarifying these concepts is key to ensuring the effective adoption and implementation of precision agriculture.

Conclusion

- Precision Agriculture (PA) transforms traditional farming into intensive, data-driven practices through the use of time- and space-varying data. It is rapidly becoming a vital component of modern, productive farming systems within dynamically changing agroecosystems. PA integrates a suite of interconnected technologies—such as GIS, GNSS, and remote sensing—that collectively improve soil and crop productivity, optimize cultivation practices, and enhance the efficiency of input usage. Over a relatively short period, PA has experienced rapid technological growth, and its applications are steadily expanding across various agricultural fields and industries.
- With tools like remote sensing, GNSS, and GIS, farmers can now regularly monitor, map, and manage spatial variability within their fields. This capability supports site-specific management (SSM) decisions that maximize input use efficiency, crop yields, and profitability, while simultaneously reducing environmental pollution. However, successful implementation of PA requires substantial technical skills, knowledge, and expertise. The high costs associated with advanced sensing and control technologies also present a barrier, making it crucial for producers to carefully select PA tools that offer the greatest return on investment under their specific conditions.
- To support wider adoption, government initiatives could offer incentives that make these technologies more accessible to farmers, recognizing their significant environmental benefits. Strengthening collaboration among farmers, industry stakeholders, extension agents, and researchers is also

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essential to drive innovation, training, and support for PA adoption. Such partnerships will ensure that PA continues to evolve as a cornerstone of sustainable and profitable agriculture.

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To Reduce Water Contamination Effectively by Employing Eco-Friendly and Sustainable Bioremediation Techniques Using Natural Processes

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Abstract

Bioremediation has a wide range of advantages, including the detoxification, reduction, degradation, or transformation of toxic chemicals into less toxic substances as part of this process. As bioremediation uses microorganisms, it is an environmentally friendly and cost-effective approach. Highly porous shorelines where nutrients and oxygenated saltwater might reach the surface and subsurface oil residue have been proven to be useful for bioremediation. Bioremediation is regarded as a safe and sustainable technology. On-site bioremediation can be carried out without significantly disrupting the environment or human activity. This research paper will discuss the application, benefits, usage and methodology for reducing the amount of contamination from water through bioremediation by using algae, fungi and spirogyra species.

Keywords: Bioremediation, algae, fungi, spirogyra.

Introduction

Bioremedation broadly classified to any process wherein a biological system (typically bacteria, fungi, algae, etc.) living or dead, is employed for removing environmental pollutants.

1. Algae

A colloquial name for a broad and varied class of eukaryotic, photosynthetic organisms. It is a polyphyletic cluster that consists of species from several different clades. The creatures covered range from single-celled microalgae like Chlorella, Prototheca, and diatoms to multicellular ones like the giant kelp, a huge brown alga that can reach lengths of up to 50 metres (160 feet). SPYROGYRA, a genus of filamentous charophyte green algae of the order Zygnematales, is being used for this project. The name of the genus comes from the helical or spiral arrangement of the chloroplasts that are unique to it.

2. Fungi

Any member of the family of eukaryotic creatures, which also includes the more well-known mushrooms and microbes like yeasts and molds. Separate from the other eukaryotic kingdoms, which according to one conventional classification include Plantae, Animalia, Protozoa, and Chromista, these organisms are categorised as a kingdom. Our Choice Is Ganoderma. In the family Ganodermataceae, the genus Ganoderma contains over 80 species of polypore fungi, many of which are native to tropical areas. They are utilised in conventional Asian treatments and have a wide genetic variety. Because ganoderma have double-walled basidiospores, they may be distinguished from other polypores. They may also be known as bracket fungi or shelf mushrooms.

3. Bryophyta

A group of land plants, sometimes treated as a taxonomic division, that contains three groups of non-vascular land plants (embryophytes): the liverworts, hornworts and mosses. In the strict sense, Bryophyta consists of the mosses only.
Bryophytes are characteristically limited in size and prefer moist habitats although they can survive in drier environments. We Are Using Funeria. Funaria is a genus of approximately 210 species of moss. Funaria hygrometrica is the most common species. Funaria hygrometrica is called “cord moss” because of the twisted seta which is very hygroscopic and untwists when moist.

Objectives

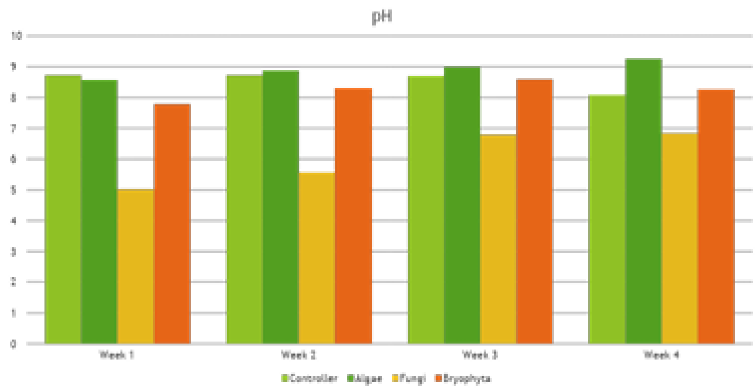
1. The main principle is degrading and converting pollutants to less toxic forms.
2. Collection of local species (algae, fungi, bryophyte) and insert different species into the water.
3. Fungi, algae and bryophyte play a major role as decomposers and symbionts in water.
4. Perform various tests to determine pH, turbidity, Conductivity and record its reading.

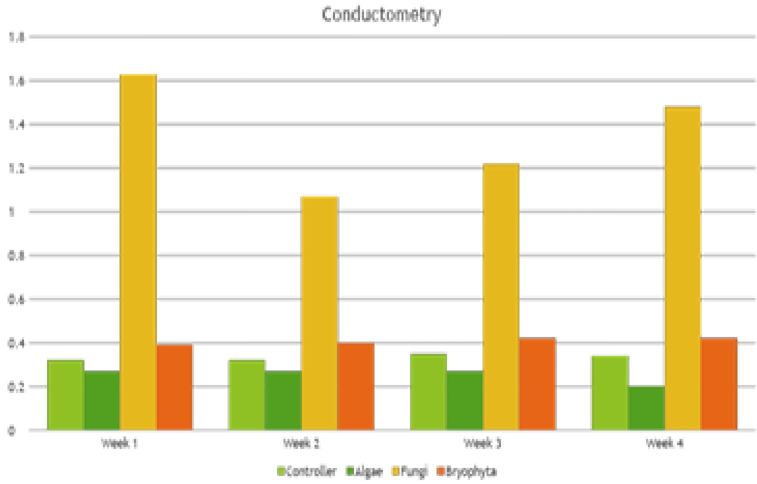
Methodology

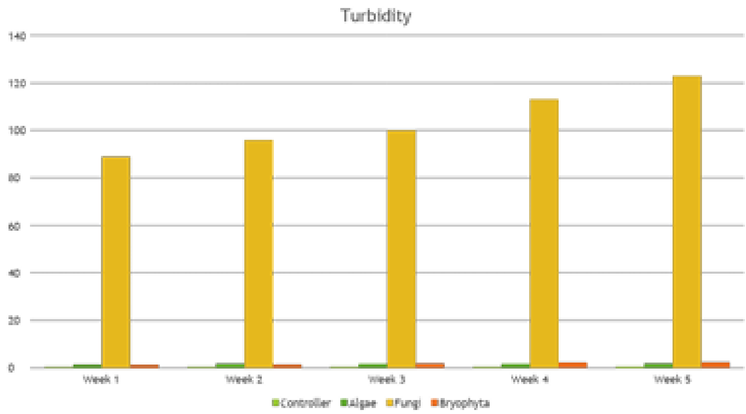
1. **Determination Acidity or Alkalinity of water. (pH):** to 100 ml of sample add 0.3ml of saturated solution of KCl. Determine the pH.
2. **Determination Conductivity of Water:** Determine the conductivity of a water sample at 250C using a suitable conductivity meter.
3. **COD of Water:** Organic substances present in the water sample are oxidised by K2Cr2O2 in acidic medium to ensure complete oxidation of the material, the sample is heated in presence of Ag2SO4 as a catalyst. To remove chloride interference, H3SO4 is used. The excess of K2Cr2O2 is titrated back against standard Ferrous alum solution. The amount of oxidisable organic matter measured as Oxygen equivalent, is proportional to the K2Cr2O2 consumed.

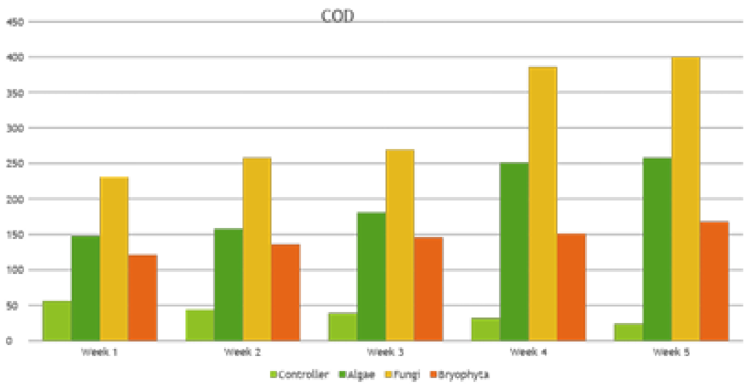
4. **Turbidity:** Determine the turbidity of water sample by using suitable turbidimeter Bioremediation broadly classified to any process wherein a biological system (typically bacteria, fungi, algae, etc.) living or dead, is employed for removing environmental pollutants.

To determine the portability of water using algae, fungi and bryophyta.









Conclusion

As by the tests performed, we conclude that Funaria (Bryophyta) is a viable species.

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Valorization of Organic Wastes Through Solid-State Fermentation for Sustainable Bio-Fertilizer Production

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Abstract

The growing demand for environmentally friendly farm practices has prompted the development of bio-fertilizers using low-cost and renewable raw material bases. The chapter discusses the preparation and potential of the bio-fertilizers from a range of waste sources, including agricultural wastes, biofuel production wastes, and industrial wastes. These bio-fertilizers are generated through inoculating useful microorganisms—nitrogen-fixing bacteria, phosphate-solubilizing bacteria, fungi, and cyanobacteria—into organic matter using solid-state fermentation (SSF), a cost-effective and efficient biotechnology process. The process harnesses the natural organic matter decomposition process, increases soil fertility, and promotes plant growth, leading to sustainable food systems production. SSF is beneficial in terms of low water usage, less processing cost, and effective use of agro-industrial waste according to circular economy. In all, bio-fertilizers are an attractive alternative option for chemical fertilizers with lower environmental footprint and enhanced soil health and agricultural productivity.

Keywords: Agriculture waste, agro-waste, organic residues, solid-state fermentation.

Introduction

The formulated bio-fertilizers prepared from economical and low-cost raw materials with the inoculation of special microorganisms present a feasible and promising market for commercialization, as well as for promoting environmentally friendly technology. This will reduce the country's reliance on chemical fertilizers to produce, increase, and sustain food production.

Preparation of bio-fertilizers using various wastes, including livestock, poultry waste and agricultural waste as the main raw materials, not only creates economic benefit for enterprises but also contributes greatly to environmental engineering. After safe treatment and fermentation, these raw materials are converted into bio-fertilizers using appropriate microorganisms. These bio-fertilizers enhance soil fertility, improve crop yields, and promote sustainable agricultural practices (Kumar, et al., 2018). By reducing the dependency on synthetic fertilizers, we can foster a healthier ecosystem while supporting farmers' livelihoods and ensuring food security for future generations. This production system not only turns waste into value but also protects the environment, aligning with circular economy principles (Artola et al., 2024). It is a cost-effective, sustainable solution that diverts production waste from landfills and returns it to the soil.

Several kinds of agro-waste are good carrier materials for microbial inoculants. The biodegradation of such materials into simple sugars provides energy sources for heterotrophic microorganisms, such as phosphate-solubilizing and nitrogen-fixing bacteria. These beneficial microorganisms play a crucial role in enhancing soil fertility and promoting plant growth, ultimately increasing crop yields (Solano Porras et al., 2023). The main inoculants include bacteria, fungi, and cyanobacteria (blue-green algae). These microbes have diverse abilities that can be exploited for better farming practices, including nitrogen fixation, decomposition of organic matter, and enhancement of nutrient availability (Yadav et al., 2021).). Some also combat diseases or break down complex soil compounds into simpler forms that plants can utilize, thereby increasing plant productivity.

Objectives

- To demonstrate that different waste materials can be used to produce bio-fertilizers.
- To understand that solid-state fermentation (SSF) is a viable technology for producing microbial products.

Agricultural Wastes

Agricultural waste (agro-waste) refers to the waste generated through various agricultural activities, including manures, bedding, plant stalks, hulls, leaves, and vegetable matter. Often considered useless and discarded, the accumulation of agro-waste poses health, safety, environmental, and aesthetic risks. These biomasses have great potential as alternative, beneficial inputs for sustainable agriculture due to their high moisture content, organic matter, and mineral content (Saleem, 2022).

Agro-industrial wastes are rich in nutrient composition and bioactive compounds, including insoluble constituents (cellulose, lignin) and soluble components (sugars, amino acids, organic acids). Other compounds include fats, waxes, resins, pigments, proteins, and minerals, making these residues suitable as raw materials for industrial processes (Tripathy, & Mishra, 2016).

Such residues offer ideal conditions for microbial growth. Microorganisms reuse these wastes as substrates via solid-state fermentation (SSF), a simple and cost-effective method (Sharma, et al., 2022). Hence, agro-wastes are the cheapest resources farmers can use to improve soil fertility, recycle waste, and contribute to an eco-friendly environment.

Industrial Wastes

A significant quantity of organic residues and effluents is produced annually by food-processing industries such as juice, chips, meat, confectionery, distilleries, and breweries. These residues, rich in cellulose, hemicellulose, lignin, nitrogen, and carbon, are ideal for bioconversion into bioethanol, biogas, and other commercial products (Bratovcic, A. 2025).

India produces substantial quantities of apples, cotton, soybeans, and wheat, leading to a corresponding increase in waste generation. Many of these industrial wastes remain unutilized, adversely impacting the environment. However, their composition makes them ideal for conversion into value-added products. For example, oil cakes from oil-extraction industries (e.g., canola, sunflower, coconut, mustard, soybean, cottonseed) are rich in nutrients and low-cost, making them suitable substrates for SSF (Sarkar, 2021).

In Morocco, a combination of fish, brewing, and brandy industry wastes was used in SSF with Saccharomyces cerevisiae—a yeast recovered from brewery tanks—for its fermentative and probiotic properties (Łukaszewicz, 2024).

Solid-State Fermentation (SSF)

SSF is a biotechnological fermentation process where microorganisms grow on non-soluble materials or solid substrates under controlled conditions with little to no free water. SSF is widely used to produce microbial products such as food, feed, fuel, chemicals, and pharmaceuticals (Artola et al., 2024). The solid substrates provide a favourable environment for microbial flora, including bacteria, fungi, and yeast.

SSF is appreciated for its simplicity, use of low-cost biomaterials, minimal pretreatment needs, low wastewater generation, and the ability to mimic natural microenvironments favourable to microbial growth (El Sheikha & Ray, 2023). Moisture content is a critical factor influencing microbial growth and metabolite biosynthesis in SSF. Common substrates include cereal grains (e.g., rice, wheat), legume seeds, wheat bran, and lignocellulosic materials (e.g., straws, sawdust).

Low water activity in SSF offers advantages like easy product recovery, lower production cost, reduced fermented size, and minimized energy needs for stirring and sterilization. Factors such as microorganism selection, solid support, water activity, temperature, aeration, and fermenter type are crucial for successful SSF operations (Singhania, 2017).

Microorganisms in SSF may occur as pure or mixed cultures. Some SSF processes (e.g., tempeh production) require specific molds that thrive under low-moisture conditions, relying on extracellular enzymes for fermentation (Kumar, 2024).

SSF involves several steps (Fig 1):

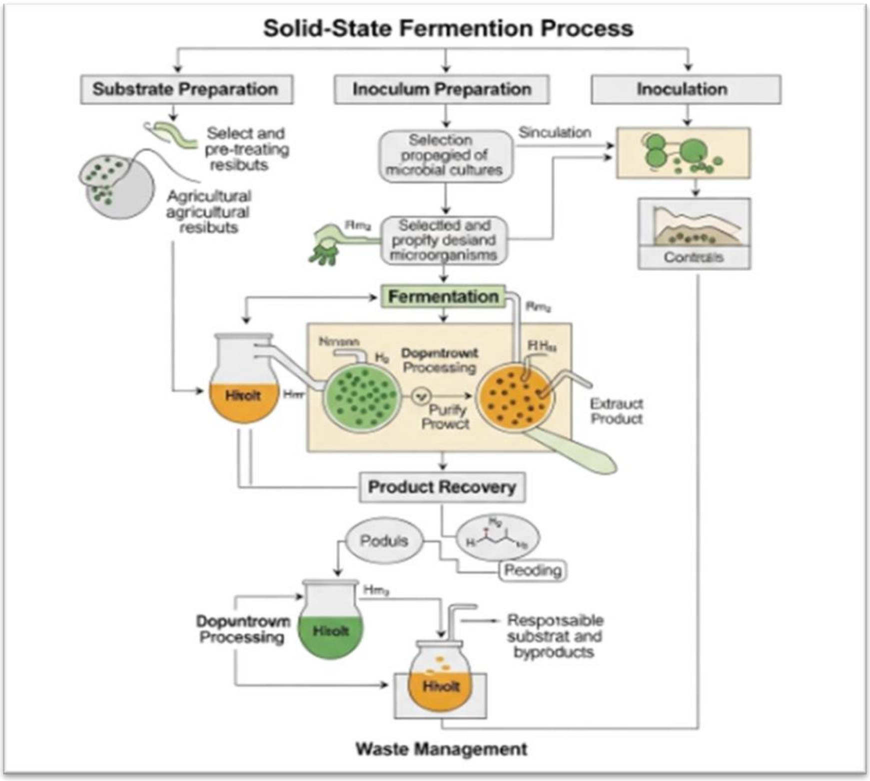

Fig 1. Solid state fermentation process.

1. Selection of substrate.
2. Substrate pre-treatment (mechanical, chemical, or biochemical) to increase nutrient availability.
3. Hydrolysis of polymers (e.g., polysaccharides, proteins).
4. Fermentation of hydrolysates.
5. Downstream processing for purification and product quantification.

Several factors are essential in bio-fertilizer production, such as the microbial growth profile, optimum conditions, and formulation techniques. The process involves six major steps: selecting active organisms, isolating and selecting target microbes, choosing the method and carrier material, selecting propagation method, prototype testing, and large-scale testing.

Bio-fertilizers are commonly prepared as carrier-based inoculants. Incorporating microorganisms into carrier materials facilitates easy handling, storage, and high effectiveness (Sarbani& Yahaya 2022). Sterilization of carriers (via gamma irradiation or autoclaving) is vital to maintain high inoculant viability and prevent contamination.

Suitable carrier materials should be inexpensive, non-toxic, abundant, and able to retain moisture and adhere well to seeds. They should also offer pH buffering capacity and be easily sterilizable.

Conclusion

SSF is a promising technique for producing efficient, economical bio-fertilizers using agricultural, biofuel, and industrial wastes. These bio-fertilizers support crop yield, reduce dependence on chemical fertilizers, and contribute to sustainable agricultural systems by optimizing waste resource use and generating income.

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Green Energy and Sustainable Fuel Technologies: Pathways to a Low-Carbon Future

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Abstract

The adverse environmental effects of using fossil fuels have led to a paradigm shift towards finding alternative solutions, while the ever-increasing demand for energy has made this search far more sophisticated. The technologies that focus on climate change mitigation, reduction in carbon footprints and sustain global ecosystems economically are referred to as green energy or sustainable fuels technologies. These include renewable sources such as solar power, wind, hydroelectric power, geothermal energy and biomass which are clean and self-replenishing. Green hydrogen, biofuels as well as synthetic fuels are other technologies that can be used in place of petroleum-based products especially in the transportation and industrial sectors.

Government programs, technological developments, and heightened environmental awareness all support green energy initiatives. The integration of renewable energy sources into existing energy systems is being facilitated by advanced storage technologies, smart grids, and higher levels of energy efficiency. Nevertheless, large scale implementation is still greatly hindered due to policies lacking in support, high capital costs, the necessity for supportive regulations and intermittency.

This chapter we see in to great detail various types of green energy and the growth of sustainable fuel technologies, also we see the roles they play in shaping a sustainable and resilient energy future. Also, in its report of social, economic and environmental issues related to these technologies which we put in to play the key roles of policy makers, industries, and individuals in the global energy shift. In the end it is very much so that which we put into green energy and sustainable fuels that will have us see success in terms of long-term environmental health, energy security, and economic stability.

Keywords: Government programs, renewable sources, green energy, economic stability.

Introduction

The world is at a crossroads as it transforms which energy sources it supports in response to the dual issues of climate change and energy security. For more than a century fossil fuels coal, oil, and natural gas have been the main players in global energy use which while they have powered economic growth also have put out large amounts of greenhouse gases, air pollution, and environmental damage into the mix. The International Energy Agency (IEA, 2023) reports that the energy sector is at present the source of about 73% of our global emissions which in turn has made it the primary target for climate change mitigation efforts.

Green energy that comes from renewable resources and sustainable fuel technologies is at the fore of this energy transition. We see that output of green energy sources like solar, wind, hydropower, geothermal, and biomass which nature renews on its own and which in turn has minimal environmental impact. These sources not only put forth an alternative to depleting resources but also play a role in creating a cleaner more sustainable energy system. As reported by the Intergovernmental Panel on Climate Change (IPCC, 2022) large scale and quick deployment of renewable energy is key to achieving a 1.5-degree temperature rise.

Solar energy uses sunlight through photovoltaic (PV) cells and concentrated solar power systems, offering a clean and rapid cost-effective energy solution. Wind energy uses turbine to catch kinetic energy from atmospheric currents, contributing significantly to the electrical mixture in many countries. Hydropower, the most established form of renewable energy, generates electricity from the gravitational force of flowing water. The geothermal energy taps the Earth's internal heat, while biomass energy uses organic materials for power generation and biofuel production. Each of these sources plays an important role in diversifying energy supply and reducing carbon emissions.

Continuous fuel technologies are complementary to green electricity by dechroming areas that are difficult for electrification such as transportation, aviation and heavy industries. Bio fuel plants such as ethanol and biodiesel are generated from materials and waste, providing renewable options for gasoline and diesel. Green hydrogen produced through electrolysis operated by renewable energy can serve as a clean fuel for vehicles, industrial processes and energy storage. Synthetic fuel, derived from captured carbon dioxide and hydrogen, with mimic fossil fuel but quite low life cycle emissions.

Technological progress is central for scalability and efficiency of green energy systems. Innovations in battery storage, such as lithium-ion and flow batteries, address the intermittent of solar and wind energy by storing additional energy for use during low generation periods. Smart grid technologies enable real -time monitoring and managing energy flow, increasing the grid reliability and integration of diverse energy sources. Additionally, decentralized energy systems and microgrid communities are empowered to generate and manage their energy, increase flexibility and reduce transmission losses.

Economic factors also play an important role in adopting green energy. The cost of solar and wind technologies in the last decade has declined dramatically, making them cheaper or even cheaper than fossil fuels in many areas (Irena, 2023). Investment in renewable energy generates employment, stimulate local economies, and reduce dependence on imported fuel. In addition, green energy projects often include low operation and maintenance costs, further enhancing their economic attraction.

However, infection for green energy is not without obstacles. Intimacy, land use conflicts, supply chain boundaries for important minerals, and the need for grid modernization faces significant challenges. Financial obstacles, policy uncertainty and resistance from handy fossil fuel industries can also progress slow. To address these issues, coordinated efforts are required between governments, private sectors, researchers and civil society.

The importance of policy framework cannot be eliminated. Effective policies, including subsidy, tax encouragement, renewable portfolio standards and carbon pricing, are required to run investment and innovation. International agreements such as Paris Accord provide a global structure for cooperation and accountability. Public engagement and education are equally important for building social support and running behavioural change towards permanent energy practices.

Finally, green energy and permanent fuel technologies are not only options for fossil fuels, but are essential components of a permanent future. Their development and integration in global energy mixture is necessary to reduce climate change, increase energy security and promote inclusive economic growth. The following sections of this chapter examine their benefits, challenges and future prospects, in depth in specific types of specific types of specific types and durable fuels.

Solar and Wind Energy

Solar and wind energy represents the fastest growing segments in the global renewable energy market. Their widespread adoption is attributed to their environmental benefits, technical maturity and declining costs. These energy sources are important to reduce power generation and achieve climate goals.

Solar energy uses the power of the sun through photovoltaic (PV) panels and concentrated solar energy (CSP) systems. PV technology converts direct sunlight into electricity using semiconductor materials, while CSP uses mirrors or lenses

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to focus on sunlight on a receiver that produces steam to run turbines. According to Ren21 (2023), the global solar PV capacity exceeded 1,100 GW by the end of 2022, which contributes significantly from countries such as China, the United States and India.

Wind energy is captured using wind turbines that transfer the kinetic energy of the air to mechanical strength and then electricity. Onshore wind fields are common in areas with continuous wind patterns, while the offshore wind fields have exploited strong and more stable winds on the oceans. The global wind capacity reached 837 GW in 2022, with technical reforms and rapid growth operated by tributaries (GWEC, 2023).

Both solar and wind energy are characterized by zero fuel costs, low operating expenditure and minimum environmental footprints. They contribute to energy diversification, reduce greenhouse gas emissions, and increase energy security. However, they also encounter challenges such as intercness, which can affect grid stability. Solutions include hybrid systems, grid interconnections, demand-side management and energy storage technologies.

Policy support has been an important contributor to the expansion of solar and wind energy. Incentives such as feed-in tariffs, tax credit and renewable energy auction have inspired investment and innovation. As the technology continues to move forward and the cost falls, solar and wind are expected to dominate future power generation, which paves the way for a permanent and flexible energy system.

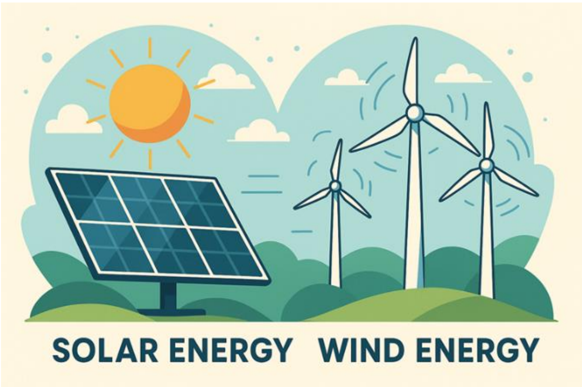

Figure 1: Solar energy and wind energy

Bioenergy and Biofuels

Bio -organic is derived from organic materials and represents one of the most versatile forms of renewable energy. This includes bioelectricity, biogas and liquid biofuels, and it plays an important role in reducing dependence on fossil fuels, especially in areas such as transport, heating and rural electrification.

The first generation of biofuels, such as ethanol and biodiesel, corn, sugarcane and soybean oil, are produced from food crops. These fuels are already used as gasoline or diesel mixtures in many countries, which contributes to emission cuts. However, they raise concerns about food security, land use and deforestation. The second generation of biofuels, which are obtained from lignocellulos biomass such as agricultural residues and forestry waste, offer more durable options using non-eating feedstocks. The third-generation bio fuel, depending on algae, promises even more stability with high yields and minimal land requirements (IEA bioenergy, 2023).

Biogas is another important bioenergy form, produced through anaerobic digestion of organic waste materials such as animal manure, food waste and sewage mud. It is mainly made of methane and can be used for cooking, heating and power generation. Biomass can also be combined directly or to produce sinks and bio-oil through gasification and pyrolysis, its usefulness can be expanded.

Despite its benefits, bio -organism faces stability challenges related to feedstock supply, land use conflicts and life cycle emissions. Stability certification schemes and integrated land-use schemes are required to ensure responsible bioenergy development. In addition, enzymes are important for improving technological innovation efficiency and reduced costs in algae cultivation.

Bioenergy provides decentralized energy solutions and promotes rural development, especially in developing countries. With the right policy structure, it can contribute significantly to a low carbon energy infection and complement other renewable sources in a diverse energy portfolio.

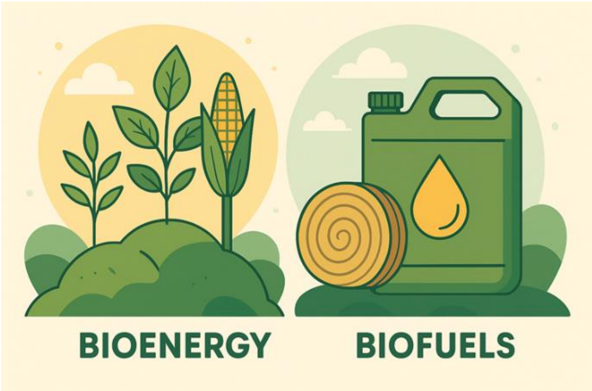

Figure 2: Bioenergy and Biofuels

Green Hydrogen and Synthetic Fuels

Green hydrogen and synthetic fuels are emerging as vital components of deep decarbonization strategies, particularly for hard-to-abate sectors such as heavy industry and long-haul transport. Green hydrogen is produced through the electrolysis of water using electricity from renewable sources, resulting in zero direct greenhouse gas emissions (International Energy Agency [IEA], 2021).

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Synthetic fuels, on the other hand, are produced by combining carbon dioxide—typically captured from industrial processes or the atmosphere—with green hydrogen, yielding a liquid fuel that can substitute gasoline, diesel, or jet fuel (IRENA, 2021).

Green hydrogen has versatile applications. It can be used in fuel cells to power vehicles, in industrial processes such as steel and ammonia production, and as a means of storing surplus renewable electricity (Hydrogen Council, 2022). Fuel cells, particularly proton exchange membrane (PEM) types, convert hydrogen into electricity efficiently and with zero emissions. These technologies are now being integrated into buses, trucks, trains, and stationary power systems (IEA, 2021).

Synthetic fuels offer a carbon-neutral alternative to fossil fuels and are compatible with existing internal combustion engines and fuel infrastructure, making them attractive for short- to medium-term transitions (IRENA, 2021). Despite the potential, the widespread adoption of green hydrogen faces challenges such as high production costs, limited infrastructure, and substantial renewable energy requirements (IEA, 2021). Key areas of ongoing research include improving electrolyzer efficiency, hydrogen storage solutions, and pipeline distribution networks (IRENA, 2021).

To scale up green hydrogen and synthetic fuels, strong policy support, international collaboration, and public-private partnerships are crucial. As costs decline and infrastructure expands, these fuels are poised to play a transformative role in achieving net-zero emissions and supporting a circular carbon economy (Hydrogen Council, 2022; IEA, 2021).

Figure 3: Green Hydrogen and Synthetic Fuels

A comprehensive visual observation of green energy and Sustainable fuel technologies shows six essential components that form a permanent energy for the future backbones. Solar energy and wind energy are presented as the most prominent forms of renewable energy, which uses the natural forces of sunlight and air to generate electricity through photovoltaic panels and wind turbines. These sources are important in reducing dependence on fossil fuel and reduce greenhouse gas emissions (Twidel and Veer, 2015). Biofuels, which are derived from organic materials such as agricultural crops, plant residues and municipal waste, serve as a cleaner option for traditional petroleum-based fuels and are being used in rapid transportation and industrial areas (Demirbas, 2009). Hydrogen fuel represents a state-of-the-art innovation in clean energy, using fuel cells as the only by-product to convert hydrogen gas into electricity, thus offering a highly durable and emission-free energy solution (dinner and ACAR, 2015). Waste-to energy technologies add another important dimension by converting municipal and industrial waste into exercising power, making the needs of both energies and waste management challenges together (Kumar et al., 2011). Finally, the importance of energy storage systems is emphasized, highlighting technologies such as advanced batteries and smart grids that help balance energy supply and demand, increase grid stability, and ensure reliability of internal sources such as solar and wind (Luo et al, 2015). Collectively, these technologies not only support infections in the low carbon economy, but also significantly contribute to energy security, environmental protection and long -term stability.

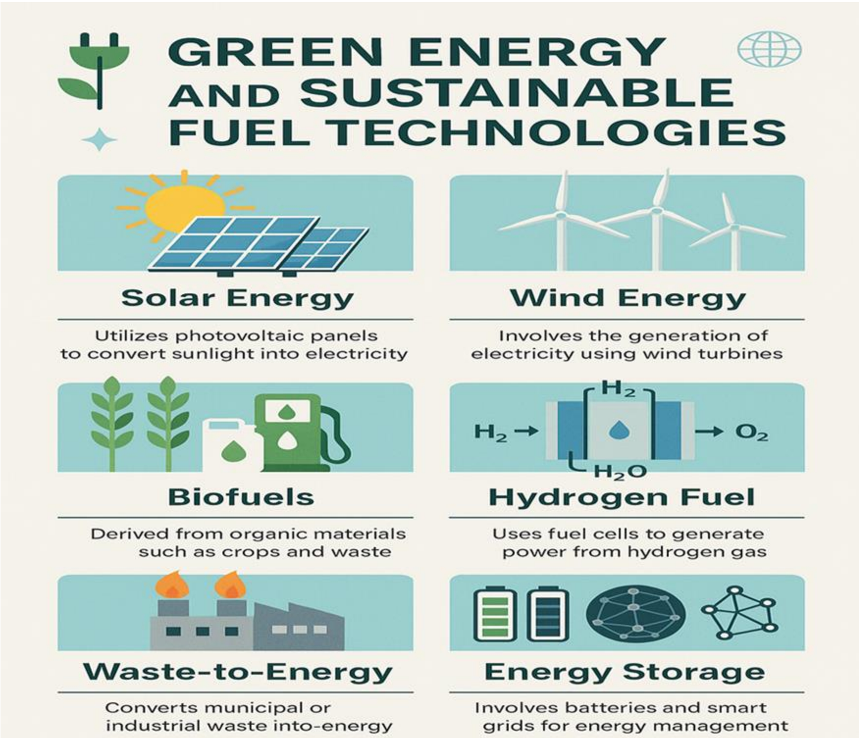

Figure 4: Green Energy and Sustainable Fuel Technologies

Conclusion

Green energy and permanent fuel technologies are central to address the 21st century environment, economic and social challenges. They provide viable solutions to reduce greenhouse gas emissions, increase energy security and promote inclusive economic growth. Solar and wind power is leading the changes of power generation, while bioenergy, green hydrogen and synthetic fuels provide permanent options for areas that are difficult to electrify.

Infection in a permanent energy system is not without challenges. Issues of sustainable energy system such as intermittency, infrastructure intervals, resource obstacles and policy uncertainties require extensive strategies and multi-non-non-non-non-non-non-non-non-non-cooperation. Innovation, investment and public engagement will be important in overcoming these obstacles and intensifying the deployment of clean energy solutions.

Government policies and international agreements should prioritize renewable energy development, carbon pricing and stability standards. Businesses need to embrace cleaner technologies and durable practices, while individuals can contribute through informed options and advocacy. It is also necessary to increase education and awareness to run public support and behaviour change.

Finally, wide adopting green energy and durable fuel technologies is necessary to achieve climate goals, protect the ecosystem and ensure a rich future for all. Global energy infection is a challenge and an opportunity - an opportunity to create a flexible, equitable and environmental sound energy system for the coming generations.

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Green Technologies in Pharmaceutical and Agrochemical Industries

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Abstract

Green technologies are reshaping the pharmaceutical and agrochemical industries by introducing sustainable and environmentally conscious alternatives to traditional chemical processes. Historically, these fields have contributed to significant contributors to environmental pollution through excessive use of hazardous solvents, energy-intensive manufacturing, and generation of toxic waste. The chapter provides a thorough review of the application of green chemistry concepts into pharmaceutical and agrochemical practices.

Innovative methodologies Involving processes like biocatalysis, microwave-assisted synthesis, continuous flow chemistry, eco-friendly solvents and analytical technologies for process monitoring (PAT) are explored in depth. These methods provide considerable advancements in minimizing environmental impacts while concurrently enhancing process efficiency, safety, and scalability. In the agrochemical domain, the adoption of biopesticides, nano formulations, controlled-release fertilizers, and bio-fertilizers is gaining momentum, promoting safer crop protection and nutrient delivery systems. These technologies not only reduce ecological disturbance but also enhance yield and resource efficiency in sustainable farming.

Real-world case studies are used to illustrate the practical applications and effectiveness of these technologies. For example, Pfizer's greener synthesis of sertraline demonstrates process optimization and waste reduction in pharmaceuticals, while Syngenta's development of a biodegradable herbicide highlights sustainable innovation in crop protection. The chapter also evaluates the advantages for the environment and the economy of adopting green technologies, this includes lower operational expenses and enhanced effectiveness, regulatory compliance, and positive corporate social responsibility outcomes. Challenges in widespread implementation such as high initial investment, regulatory barriers, and technological complexity are critically examined. Finally, the chapter discusses emerging trends and future prospects involving artificial intelligence, blockchain for enhancing supply chain transparency, advanced materials, and the establishment of integrated biorefineries. The incorporation of eco-friendly technologies is essential not only for achieving global sustainability objectives but also for ensuring competitiveness in changing markets.

Keywords: Green chemistry, Biocatalysis, Sustainable manufacturing, Agrochemicals, Environmental innovation.

Introduction

The advancements in technology during the 20th and 21st centuries have greatly changed the pharmaceutical and agrochemical industries. These industries have been pivotal in addressing global health challenges and boosting agricultural productivity. Nonetheless, this advancement has not been achieved without environmental costs. The widespread use of synthetic chemicals, reliance on non-renewable resources, generation of hazardous waste, and emissions of greenhouse gases have expressed important issues regarding environmental sustainability and public health [1].

In response to these challenges, the concept of green technology has emerged as a vital tool for reforming traditional industrial practices. Green technologies refer to environmentally friendly innovations that promote sustainability by

minimizing pollution, conserving energy and resources, and enhancing safety. These technologies are rooted in the principles of green chemistry a field dedicated to designing products and processes that reduce or eliminate the use and generation of hazardous substances [2].
This chapter provides an in-depth exploration of how green technologies are revolutionizing pharmaceutical and agrochemical industries. The chapter explores major innovations along with their methods of implementation, associated advantages, challenges faced, and potential future developments. Practical relevance and effectiveness are demonstrated through real-life examples and case studies [3–7].

The Foundation of Green Technologies

Green Chemistry, often referred to as sustainable chemistry, was formally introduced by Paul Anastas and John Warner during the 1990s. It is based on a series of foundational principles aimed at minimizing the harmful effects of chemical production and use on both the environment and human health [8]. The Twelve Principles of Green Chemistry are:

1. **Waste Prevention:** Emphasize strategies that eliminate the generation of waste at the source instead of relying on its treatment or disposal after formation.
2. **Atom Efficiency:** Develop chemical synthesis routes that ensure the maximum conversion of raw materials into the desired end product, thereby reducing byproducts and inefficiencies [9].
3. **Less Hazardous Chemical Syntheses:** Utilize and produce materials that are minimally toxic to human health and the environment.
4. **Designing Safer Chemicals:** Create chemical products that are effective while also lowering toxicity levels.
5. **Safer Solvents and Auxiliaries:** preferring or deciding in favour of options that are safer for health and the environment
6. **Energy Efficiency:** Reduce energy consumption and carry out reactions at ambient temperature and pressure.
7. **Use of Renewable Feedstocks:** Choose raw materials that are renewable instead of depleting resources.
8. **Reduce Derivatives:** Sidestep unnecessary derivatization (the use of blocking or protecting groups).
9. **Catalysis:** Employ catalytic agents that are as selective as possible.
10. **Design for Degradation:** Chemical products should decompose into harmless substances.
11. **Real-time Analysis for Pollution Prevention:** Monitor and regulate processes in real time.
12. **Inherently Safer Chemistry for Accident Prevention:** Select substances

and forms that reduce risk.

These principles form the backbone of green technologies in pharmaceutical and agrochemical industries, guiding the development of safer, cleaner, and more efficient processes and products [12].

Green Technologies in The Realm of Pharmaceuticals.

The pharmaceutical sector has historically depended on processes that are resource-intensive and produce significant waste. However, growing environmental regulations, public awareness, and economic incentives have driven the adoption of green technologies across the drug development and manufacturing pipeline [13].

Green Synthesis Techniques

a. Biocatalysis

Biocatalysis uses biological catalysts mainly enzymes to perform chemical reactions. These catalysts exhibit a high degree of specificity, operate under mild conditions and often do not require hazardous solvent conditions and, the use of lipase enzymes during the process of synthesis of enantiomerically pure intermediates has become a standard in producing cardiovascular and anti-inflammatory drugs. The preparation of the chiral intermediate for atorvastatin using Ket reductase is a well-known example [14].

b. Microwave-Assisted Organic Synthesis (MAOS)

MAOS improves reaction speeds through the use of microwaves irradiation, which provides rapid and uni-form heating. This technique reduces reaction durations decreased from hours to minutes and often improves yields and selectivity. MAOS has been utilized in the production of anticancer drugs like imatinib, showing reduced energy usage and waste generation [15].

c. Ongoing Flow Chemistry

Current flow reactors allow reactions to proceed in a flowing stream, offering superior regulation of response parameters. These systems are inherently safer and enable improved scalability and automation. Flow chemistry has been utilized in the fabrication of APIs like artemisinin, a potent antimalarial, using photochemical oxidation in flow reactors [16].

Green Solvents and Reagents

Replacing traditional solvents with greener alternatives is a major focus in pharmaceutical chemistry. Conventional solvents like dichloromethane and acetonitrile pose health and environmental hazards.

- Water is used in peptide synthesis and crystallization processes.

- Ethanol, derived from biomass, is increasingly used in extraction and purification.
- Supercritical CO_2 is employed in drug particle formation and extraction, especially in producing decaffeinated coffee.
- Ionic liquids offer tunable properties and are used in electrochemical applications and catalysis [17].

Process Analytical Technology (PAT)
PAT involves real-time monitoring of chemical and physical parameters during manufacturing. This minimizes the necessity for off-line quality testing, improves product consistency, and minimizes waste. Spectroscopic techniques such as NIR, Raman, and FTIR are commonly used in PAT systems for monitoring reactions and controlling crystallization and drying processes [18].

Green Technologies in the Agrochemical Industry

Biopesticides and Biofertilizers
Biopesticides are naturally derived agents that control pests without harming beneficial organisms or accumulating in the environment. Examples include:

- Insecticides derived from neem that interfere with the growth and reproductive processes of insects.
- Bt toxins from Bacillus thuringiensis, used in genetically modified crops [19].

Biofertilizers promote plant growth by fixing atmospheric nitrogen, solubilizing phosphates, or producing growth-promoting substances. *Azospirillum* and Insecticides derived from neem that interfere with the growth and reproductive processes of insects.

Controlled-Release and Nano formulations
Controlled-release formulations provide a steady supply of active ingredients, enhancing efficacy and reducing environmental impact. Nanotechnology is enabling the development of nano pesticides and nano fertilizers with increased absorption, reduced dosage, and better targeting. For example, nano-encapsulated herbicides can penetrate plant cuticles more effectively, reducing run-off [20-21].

Green Synthesis of Agrochemicals
Green synthesis methods for agrochemicals involve aqueous-phase reactions, biocatalysis, and the use of renewable feedstocks. One example is the enzymatic hydrolysis of phosphate esters in producing organophosphates with minimal toxic byproducts [19].

Integrated Pest Management (IPM)

IPM promotes a holistic approach to pest control, integrating biological controls, crop rotation, mechanical weeding, and minimal use of synthetic chemicals. Governments and NGOs are increasingly promoting IPM to reduce pesticide dependency. The use of predator insects like ladybugs and parasitoid wasps to control aphid populations exemplifies this approach.

Case Studies

1. **Pfizer's Sertraline Process Redesign**

Pfizer re-engineered the synthesis of the antidepressant sertraline using a greener process. By switching to a biocatalytic route and optimizing crystallization, the company achieved a 50% reduction in solvent use and improved overall yield [22].

2. **Syngenta's Biodegradable Herbicide Formulation**

Syngenta's development of a biodegradable herbicide involved replacing conventional surfactants with plant-based, biodegradable ones. Field trials showed equivalent efficacy with reduced environmental persistence, making the product safer for aquatic life and groundwater.

Environmental and Economic Benefits

Green Technologies Offer Numerous Environmental Benefits:

- Reduction of toxic emissions and waste
- Lower water and energy use
- Improved biodiversity and ecosystem health

From An Economic Perspective:

- Waste reduction translates to lower disposal costs
- Efficient processes reduce raw material and energy expenses
- Enhanced product quality and regulatory compliance avoid penalties and recalls

According to a 2011 report by the American Chemical Society, implementing green chemistry strategies in pharmaceutical manufacturing can save up to $1 billion annually across the industry [23].

Challenges in Implementation

Despite clear benefits, the transition to green technologies is not without hurdles:

- **Economic barriers:** Initial R&D and infrastructure investments are high
- **Technical issues:** Adapting traditional processes to new technologies can be complex
- **Regulatory complexities:** New technologies may face delays in approval
- **Market resistance:** End-users may be skeptical of product efficacy

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- **Skill gaps:** Need for workforce training in green chemistry principles [24].

Future Prospects

The future of green technologies lies in interdisciplinary innovation. Key trends include:

- AI and machine learning to predict and optimize reaction pathways
- Blockchain for tracking and verifying sustainable practices in supply chains
- Biorefineries to produce chemicals from agricultural and forest residues
- Green engineering integrating process design with environmental metrics
- Legislative support through green procurement policies and tax incentives

International frameworks like the UN Sustainable Development Goals (SDGs) also provide a blueprint for aligning green innovations with global priorities.

Conclusion

Green technologies are reshaping the pharmaceutical and agrochemical industries, offering pathways to cleaner, safer, and more sustainable practices. By adopting green chemistry principles, these sectors can achieve environmental compliance, economic efficiency, and enhanced societal trust. The integration of scientific innovation, policy support, and stakeholder collaboration will be key to mainstreaming green technologies in the decades to come.

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In Vitro Meat: A Sustainable Future for Global Food Production

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Abstract

In the face of pressing environmental, ethical, and health challenges, the global food industry is undergoing a transformative shift. One of the most groundbreaking innovations driving this change is in vitro meat, also referred to as cultured, lab-grown, or cell-based meat. Unlike traditional meat derived from raising and slaughtering animals, in vitro meat is produced by cultivating animal cells in highly controlled laboratory environments. This technology holds tremendous promise for minimizing the ecological footprint of meat production while addressing serious ethical concerns associated with animal welfare and the health risks posed by conventional animal farming. This essay delves into the multifaceted world of in vitro meat, exploring its scientific basis, advantages, challenges, current global trends, and its potential to reshape the future of food.

Keywords: Global food industry, in vitro meat, animal welfare, global trends.

What is In Vitro Meat?

In vitro meat is the result of a biotechnological process known as cellular agriculture. It begins with a small, painless biopsy taken from a living animal to obtain muscle cells. These cells are then placed in a nutrient-rich culture medium that mimics the biological conditions within an animal's body. This medium typically contains amino acids, vitamins, glucose, salts, and growth factors to support cell proliferation. As the cells multiply, they differentiate into muscle tissue—the primary component of meat.

To enhance the structure and consistency of the cultured meat, scientists employ scaffolding techniques. These scaffolds, often made from edible materials or biodegradable polymers, provide the framework for the growing muscle cells to attach, align, and mature into tissue that closely resembles the texture of conventional meat. Advanced bioreactors are used to scale up this process, providing the optimal environment for tissue growth by controlling temperature, oxygen levels, pH, and mechanical stimulation. Dutch company Mosa Meat was one of the pioneers in this field, famously presenting the world's first cultured hamburger in 2013. Though it cost around $330,000 to produce, it demonstrated the feasibility of growing meat without slaughtering animals.

Advantages of In Vitro Meat

Environmental Sustainability: Traditional livestock farming is a resource-intensive process contributing significantly to environmental degradation. It is a leading source of greenhouse gas emissions, land degradation, water pollution, and deforestation. According to a study by the University of Oxford, producing cultured meat could reduce land use by more than 90% and greenhouse gas emissions by up to 96% compared to conventional meat production. Furthermore, in vitro meat requires significantly less water and feed, thus preserving natural resources.

For instance, the production of one kilogram of beef from cattle typically requires over 15,000 litters of water. In contrast, cultured meat could achieve the same yield using a fraction of that amount. As a result, cultured meat is poised to become a more sustainable protein source in a world increasingly threatened by climate change and resource scarcity.

Animal Welfare: One of the most compelling arguments for in vitro meat is its potential to eliminate animal suffering. Unlike traditional meat, cultured meat is produced without slaughtering animals. A single biopsy from a cow or chicken can generate thousands of kilos of meat, effectively reducing the need for mass animal farming and killing. This humane alternative aligns with growing global concerns about animal rights and ethical food production.

Organizations such as People for the Ethical Treatment of Animals (PETA) and the Humane Society have expressed cautious optimism toward lab-grown meat as a cruelty-free solution. Additionally, this technology offers a middle ground for consumers who wish to reduce animal cruelty without giving up meat entirely.

Food Security and Global Hunger: Cultured meat offers a way to decouple meat production from geography and climate. Since it can be produced in controlled environments, it allows for the local manufacturing of meat in regions unsuitable for traditional agriculture. This decentralization of production could play a crucial role in improving food security and resilience in the face of climate-induced disruptions.

Imagine a scenario were desert nations, previously dependent on imports for meat, can produce lab-grown beef or chicken in local facilities. This ability would reduce dependency on complex global supply chains and ensure more stable food supplies in the face of political or environmental crises.

Health and Safety Benefits: Lab-grown meat offers several health-related advantages. Traditional meat often contains antibiotics and hormones, which can contribute to antibiotic resistance in humans. It also carries the risk of contamination by pathogens like E. coli, salmonella, and listeria. Cultured meat, produced in sterile, controlled environments, significantly reduces these risks.
Moreover, cultured meat can be tailored to meet specific nutritional needs. For instance, scientists can adjust fat content, enrich it with omega-3 fatty acids, or remove saturated fats altogether. Such customization can aid in combating diseases such as obesity, cardiovascular issues, and diabetes.

Challenges and Limitations

Despite its advantages, in vitro meat faces a host of challenges that must be addressed before it can become a mainstream food source.
Economic Hurdles and Production Costs: The initial costs associated with producing cultured meat are high due to expensive culture media, growth factors, and infrastructure. Although the cost of a lab-grown burger has plummeted from $330,000 in 2013 to below $10 in recent prototypes, achieving price parity with traditional meat remains a hurdle. Economies of scale, technological advancements, and alternative culture media sources (such as plant-based or synthetic mediums) are essential to bringing costs down.
For example, companies like Future Meat Technologies have reportedly reduced production costs to under $4 per 100 grams of cultured chicken, which is a promising sign for commercial viability in the near future.

Consumer Perception and Acceptance: Public acceptance is another significant barrier. Some consumers are skeptical about eating meat that originates in a lab. Concerns range from the perceived unnaturalness of the product to doubts about its taste, safety, and nutritional value. Cultural and religious beliefs may also influence consumer choices.
Effective public education, transparent labelling, and involvement of trusted authorities will be key to building trust. Celebrity endorsements and chef-led tastings—such as those conducted by Michelin-star chefs—have already begun shaping positive narratives around cultured meat.

Regulatory Frameworks: Navigating the complex web of food safety regulations is a necessary step before cultured meat can be widely commercialized. Agencies like the U.S. Food and Drug Administration (FDA), European Food Safety Authority (EFSA), and counterparts in other countries are still establishing regulatory pathways for these novel products.
Singapore became the first country in the world to approve the commercial sale of cultured meat in 2020, offering lab-grown chicken nuggets developed by Eat

Just. This milestone has encouraged other countries to accelerate their regulatory frameworks, but progress remains uneven across different regions.

Technical Challenges: Replicating the exact taste, texture, and complexity of traditional meat, particularly whole cuts like steaks or ribs, remains a significant technical challenge. While ground meats are relatively easier to produce, recreating the layered muscle, fat, and connective tissues of whole meats requires more advanced techniques.

Innovations in scaffolding materials, 3D bioprinting, and synthetic biology are being explored to address these issues. Companies like Aleph Farms are developing lab-grown steaks using 3D tissue engineering to better mimic the structure of conventional meat.

Global Landscape

Several companies and research institutions around the globe are at the forefront of the cultured meat revolution:

- **Eat Just (USA/Singapore):** The first to gain regulatory approval and commercialize lab-grown chicken.
- **Mosa Meat (Netherlands):** A pioneer in the cultured hamburger space.
- **UPSIDE Foods (formerly Memphis Meats, USA):** Backed by investors like Bill Gates and Richard Branson, focusing on scalable production of multiple meat types.
- **Aleph Farms (Israel):** Specializing in cultured beef steaks using 3D bioprinting.
- **Future Meat Technologies (Israel):** Working to drastically reduce production costs and improve scalability.

Governments are also playing a supportive role. The Netherlands, for instance, has invested millions into research grants and infrastructure for cellular agriculture. The U.S. and Israel have included lab-grown meat in national food innovation strategies.

Future Prospects

The future of in vitro meat is not just about technology but also about transforming global food systems. As innovations in renewable energy and bioengineering continue to evolve, we may see distributed micro-factories capable of producing cultured meat on-demand, even in remote locations. This would minimize transportation emissions and create local food ecosystems.

Moreover, integration with vertical farming and hydroponics could lead to fully self-sustaining urban food systems. Such integration could also contribute to preserving biodiversity, as fewer natural ecosystems would need to be converted into pasture or feed crop lands.

In addition to meat, similar cellular agriculture techniques are being explored for dairy, eggs, and seafood. Companies are developing lab-grown milk proteins, egg whites, and fish fillets, further broadening the scope of sustainable animal product alternatives.

Conclusion

In vitro meat stands as a testament to the possibilities of scientific innovation aligned with ethical and ecological imperatives. Although challenges persist in terms of cost, public acceptance, and regulatory clarity, the momentum behind cultured meat continues to build. With ongoing research, investment, and policy support, in vitro meat could revolutionize the food industry and play a critical role in addressing some of the 21st century's most urgent global challenges.

As societies strive for sustainable development, reducing carbon footprints, enhancing food security, and ensuring ethical treatment of animals, in vitro meat emerges as a beacon of hope. By embracing this novel technology, we are not only changing the way we produce food but also reimagining our relationship with the natural world.

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Green Synthesized of CdS Nanoparticles and Their Applications

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Abstract

Cadmium sulfide (CdS) nanoparticles have been successfully created in this study by employing an environmentally friendly green synthesis technique. The use of dangerous chemicals that are typically used in the synthesis of nanoparticles has replaced by the use of plant extracts that are rich in bioactive compounds as natural reducing and stabilizing agents. X-ray diffraction (XRD) and scanning electron microscopy (SEM) and EDAX demonstrated the formation of CdS nanoparticles. The uniform morphology, crystalline structure and elements present of the biosynthesized CdS nanoparticles demonstrated the efficacy of the green method. This method fits with the tenets of green chemistry and provides an affordable and sustainable alternative for producing nanoparticles, which makes it appropriate for use in photocatalysis, environmental remediation, and the biomedical industry.

Keywords: CdS, SEM, solar cells, green synthesis, non-toxic synthesis.

Introduction

The cadmium sulfide consider the most common semiconductor due to its high band gap (2.42eV) and potential applications in area of spectroscopy and electronic [1] CdS Structure classify in three type are are namely hexagonal wurtzite, high pressure rock-salt phase and cubic zinc blend, hexagonal wurtzite important among these because its st9ability and easily synthesized [2,3]. Rare earth elements possess interesting optical properties due to their good interaction with light .Pr3+ doped CdS have particles have been gained much more interest in the recent year due to their describable properties and applications in different areas. Green synthesis is a sustainable and environmentally friendly process that uses biological agents to mediate the synthesis of nanoparticles, such as microorganisms, plant extracts, or biopolymers. Phytochemicals such as flavonoids, alkaloids, terpenoids, and phenolic compounds, which function as organic reducing, capping, and stabilizing agents, are abundant in plant extracts. This encourages the formation of nanoparticles in mild conditions and does away with the need for external chemical reagents.

In recent years, the green synthesis of CdS nanomaterials using plant-based extracts has gained considerable attention due to its simplicity, low cost, environmental compatibility, and potential for large-scale production. This method not only minimizes the environmental footprint but also imparts biofunctional characteristics to the nanoparticles, enhancing their performance in various applications.

Nanoparticles are widely used in a living organism for diagnostic, treatment and drug delivery systems [4]. It is essential that the particles be synthesized in a non-toxic manner. Many kinds of research are drawn to green methods as they are easy to use, reasonable, environmentally friendly, and non-polluting. Plant extracts and bacterial metabolites were the main sources of green syntheses. On the other hand, green synthetics are less harmful, but using plant extracts and bacterial metabolites presents a problem. Allergen agents and the bacterial genome may be infected by bacterial metabolites. Even though the genome and allergen agents were absent from the plant extract, the same family exhibited variation in ingredient ratios in two distinct locations. Furthermore, compared to other parts of the same plant, each part—root, leaf, etc.—has a different kind of chemical. [5]

Semiconducting CdS nanoparticles increase the efficiency of solar cells and are used in a variety of biological applications. They are also highly sensitive to visible light detection because they are photoconductive samples in the majority of optoelectronic devices 10. 11. Because of their enhanced fluorescence and optical characteristics, they can be used to both diagnose and treat cancer. Numerous physical and/or chemical techniques, including hydrothermal and thermally dissolved methods, can be used to create nanoparticles [6]. These procedures are expensive and have a number of drawbacks, including the use of dangerous chemicals and solvents. Because of the growing need for nanoparticles, environmentally friendly, affordable, and non-toxic synthesis methods must be developed. One such method is biological or green synthesis, which makes use of microorganisms, plants [7].

Materials and Method

Materials Required

1. Cadmium salt (e.g., Cd $(NO_3)_2$ or $CdCl_2$) – cadmium ion source
2. Sodium sulfide (Na_2S) or Thiourea (CH_4N_2S) – sulfur ion source
3. Plant extract (e.g., Neem, Aloe vera, green tea, Hibiscus, etc.)
4. Distilled water
5. Beakers, hot plate, magnetic stirrer, pH meter

Preparation Of Plant Extract

After being collected and allowed to dry in the shade, Panicum sarmentosum has been crushed into a fine powder. 100 mL of distilled water has mixed with 10 g of weighed Panicum sarmentosum powder. The resultant mixture was boiled for 30 minutes at 100 °C in a water bath. Following a one-hour incubation period, the solution has filtered through Whatman No. 1 filter paper [8].

Fig.1: Flow chart of CdS nanoparticles using Green Synthesis method

Cadmium sulfide nanoparticles (CdS NPs) were prepared using a green method using plant extract. Plants are rich in organic compounds containing different functional groups that act as a source of natural products. These compounds get activated by metal atoms in a basic medium to give desired NPs [9,10]. To prepare CdS NPs, a 45ml of stock solution was prepared by adding 1g of plant extract in 45ml of distilled water. Next, 1.33g of cadmium acetate was dissolved in 35 ml of the stock solution, while 0.4g of sodium sulfide was dissolved in the remaining 10 ml of the stock solution. After it the process of titration began, add a dropwise homogenous solution of sodium sulfide from the burette to a 10ml solution of cadmium acetate taken in the flask. A greenish or bright yellow color appeared on continued stirring for about half an hour, indicating the formation of CdS NPs. The CdS NPs were processed for separation by centrifuge at 7000 rpm for about 20 minutes. The resulting paste of CdS NPs was washed thrice with distilled water, ethanol, and n-hexane to remove contaminants [11]. The purified nanoparticles of cadmium sulfide were then dried in an oven and stored in a clean bottle for further characterization and activity assessments. Further, the CdS NPs formation was confirmed by taking UV-visible spectra.

Results and Discussion

Scanning Electron Microscopy (SEM)

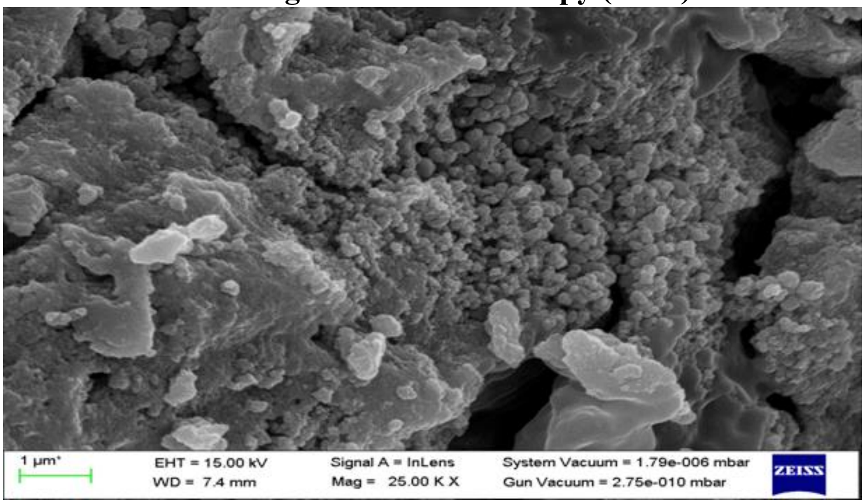

Fig. 2: SEM micrograph CdS nanoparticles

The SEM image of CdS nanoparticles prepared by green synthesis method at room temperature. The image shows in fig .2, that approximate spherical shape to CdS nanoparticle and size of the particles around 1µnm.It demonstrates clearly the formation of spherial CdS nanoparticles, and change of morphology of the nanoparticles with the Pr3+ different ions concentration.

X-ray diffraction (XRD)

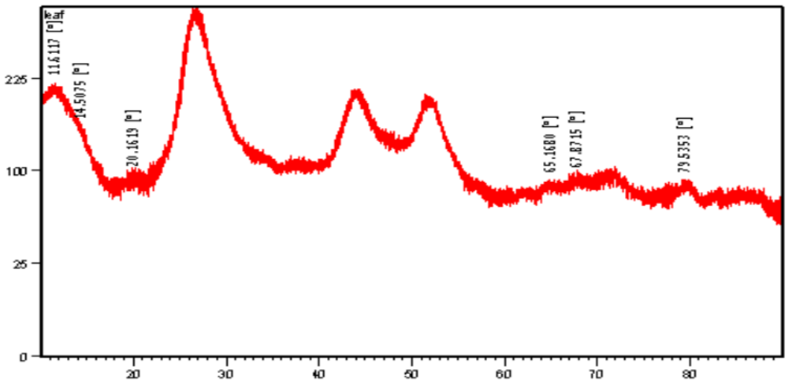

Fig. 3: XRD spectrum of CdS nanoparticles [12]

The XRD results also confirmed the proper hexagonal phase formation and improved crystallinity. In order to study structural properties of the as-green synthesis, XRD analyses have been carried out show in Fig. 3 shows the XRD patterns of CdS nanocrystals dried at room temperature. It can be seen that diffraction patterns of CdS show only diffraction peaks corresponding to hexagonal wurtzite CdS Joint Committee on Powder Diffraction Standards. No diffraction peaks related to CdS could be observed and this indicates that CdS ions have entered the CdS crystal lattice substituting the CdS ions, or entered the oxygen tetrahedral interstitials. Using the strongest diffraction peak with Scherrer formula [13]. The analysis of powder XRD pattern at room temperature shows that the sample formed is single phase with the spherical symmetry [14].

Energy Dispersive Analysis of X-Rays (EDAX)

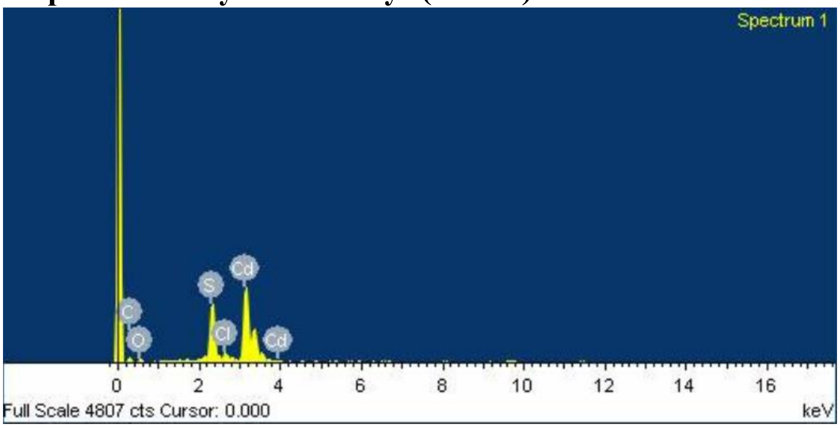

Fig. 4: EDAX spectrum of CdS nanoparticles

Repersentative EDAX spectrum of Cadmium sulfide nanoparticle has been shown in fig .4. These spectra reveal that all the elements are present in the final composition which is take initially.

Conclusion

An environmentally responsible and sustainable method of creating nanomaterials is found in the green synthesis of cadmium sulfide (CdS) nanoparticles. Plant-based extracts were used in this study as stabilizing and reducing agents, doing away with the need for dangerous chemicals that are usually employed in traditional synthesis techniques. Characterization methods like SEM, EDAX, and XRD verified that the resulting CdS nanoparticles had a controlled morphology, good stability, and promising optical properties. In addition to being in line with the ideas of green chemistry, this green synthesis method makes it possible to use CdS nanoparticles in biomedical, photocatalytic, and sensor applications. To improve yield and performance for industrial applications, more scalability and optimization research is advised.

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