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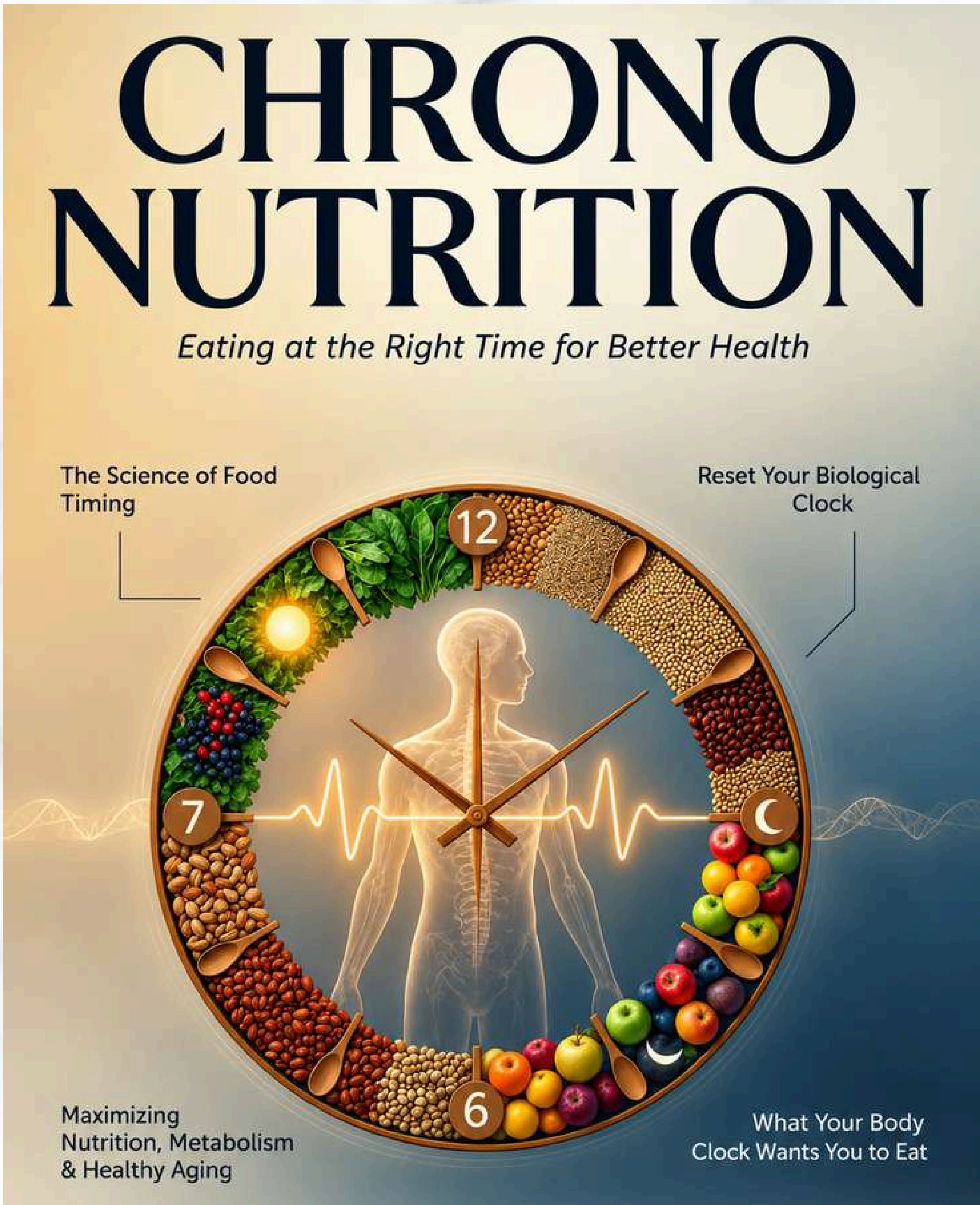

"Sync Your Plate with Your Biological Clock."

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“IT’S NOT ONLY WHAT YOU EAT—IT’S WHEN YOU EAT THAT MATTERS.”

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from the editor

In our pursuit of better health, we often focus on what we eat, how much we eat, and how nutritious our food is. Yet, an equally fascinating question is gaining attention: When should we eat?

Our bodies are not simply biological machines operating continuously at the same pace. They function according to an intricate internal timing system—the circadian rhythm, often described as our biological clock. This natural rhythm influences sleep, hormone production, metabolism, body temperature, digestion, energy utilization, and many other physiological processes. It also helps determine how our bodies respond to food at different times of the day.

This issue, “Chrono Nutrition: Eating at the Right Time for Better Health,” explores the emerging science of meal timing and metabolic health. Chrono nutrition brings together the principles of nutrition and chronobiology to understand how the timing of food intake may interact with our body's internal clock.

The concept is both simple and thought-provoking: the same food may not produce exactly the same physiological response at every time of day. Our metabolism, insulin sensitivity, digestive processes, energy expenditure, and hormonal environment change across the 24-hour cycle. Understanding these rhythms can help us think beyond conventional nutrition advice and consider a more holistic approach to healthy eating.

Through this issue, we explore how breakfast, lunch, dinner, fasting periods, sleep patterns, and daily routines interact with our biological clock. We also examine the relationship between meal timing and metabolic health, healthy aging, energy balance, sleep, and lifestyle management.

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Chrono Nutrition: Eating at the Right Time for Better Health

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Chrono nutrition is an emerging field of nutritional science that examines how the timing of food intake interacts with the body's internal biological clock, or circadian rhythm, and influences metabolic health (Garaulet & Gómez-Abellán, 2014). The human body is organized around an approximately 24-hour biological rhythm that regulates sleep, digestion, hormone secretion, body temperature, and energy metabolism. When meal timing is appropriately aligned with this natural rhythm, the body may utilize nutrients more efficiently, contributing to better metabolic health and potentially reducing the risk of chronic diseases.

Contemporary lifestyles have significantly altered traditional dietary patterns (Arble et al., 2009; Wehrens et al., 2017). Long working hours, irregular meal schedules, shift work, prolonged screen exposure, and late-night eating can disturb the body's internal clock. Such lifestyle patterns have been associated with obesity, impaired glucose regulation, hypertension, cardiovascular problems, poor sleep, and gastrointestinal disturbances. Therefore, chrono nutrition offers a simple, practical, and potentially cost-effective approach to improving dietary habits without necessarily requiring major changes in the types of foods consumed.

Different organs and tissues in the human body exhibit daily biological rhythms. The liver, pancreas, stomach, skeletal muscles, and adipose tissue perform metabolic functions that vary throughout the day. Hormones involved in hunger, insulin secretion, digestion, and energy metabolism also fluctuate according to circadian timing.

For example:

- Insulin sensitivity is generally higher earlier in the day (Sutton et al., 2018).

- The body's ability to process and utilize nutrients changes across the day.
- Metabolic activity tends to decline during the evening and night.
- During nighttime, the body shifts its physiological emphasis toward rest, repair, and restoration.

Thus, consuming meals at appropriate times may support metabolic efficiency, whereas eating large or energy-dense meals at biologically inappropriate times may place additional metabolic stress on the body.

The Biological Clock of the Body

The body's central biological clock is located in the suprachiasmatic nucleus (SCN) of the hypothalamus. It receives information about the light–dark cycle, primarily through signals originating from the eyes, and coordinates numerous physiological processes throughout the body.

The circadian system influences:

- Sleep–wake patterns
- Appetite and food cravings
- Hormone secretion
- Blood glucose regulation
- Body temperature
- Digestion and gastrointestinal activity
- Lipid metabolism
- Energy expenditure
- Immune-system functions

Importantly, food intake itself also acts as a timing signal for peripheral clocks present in organs such as the liver, pancreas, and gastrointestinal tract. Therefore, both what we eat and when we eat can influence metabolic health.

Major Principles of Chrono Nutrition

1. Start the Day with a Healthy Breakfast

Breakfast follows an overnight fasting period and can provide energy and nutrients needed to begin daily activities. Some studies suggest that consuming more calories earlier in the day may support better weight management and metabolic control (Jakubowicz et al., 2013).

However, the emphasis should be on a balanced and nutritious breakfast rather than simply increasing calorie intake. A healthy breakfast may include whole grains, pulses, milk or curd, fruits, vegetables, nuts, or other locally available nutritious foods.

2. Consume More Energy Earlier in the Day

Chrono nutrition generally encourages consuming a greater proportion of daily energy earlier in the day, when glucose tolerance and insulin sensitivity tend to be more favorable. A nutritious breakfast and adequate lunch can therefore form the major meals of the day.

This does not mean that everyone must follow exactly the same calorie distribution. Individual energy requirements, occupation, age, health status, and lifestyle should also be considered.

3. Eat Dinner Early and Keep It Light

Dinner is preferably consumed 2–3 hours before bedtime, allowing sufficient time for digestion before sleep. Heavy, fried, highly processed, and sugar-rich foods should preferably be avoided close to bedtime.

A light dinner containing vegetables, whole grains, pulses, or other nutrient-dense foods can be a better choice than a large, energy-dense meal late at night.

4. Maintain Regular Meal Timing

The human body functions more efficiently when daily routines are reasonably consistent. Eating meals at approximately similar times each day may help maintain regular patterns of hunger, digestion, and glucose regulation.

Irregular meal timing can interfere with normal metabolic rhythms. Therefore, consistency is more important than perfection.

5. Avoid Unnecessary Late-Night Snacking

Television viewing, smartphone use, prolonged working hours, and stress have contributed to the increasing habit of late-night snacking. Chips, sweets, fast foods, sugary beverages, and other energy-dense snacks are commonly consumed at night but may provide relatively few essential nutrients.

Replacing late-night snacking with healthier daytime eating patterns can support better metabolic health and may also improve sleep quality.

Health Benefits of Chrono Nutrition

1. Weight Management

Appropriate meal timing, particularly consuming meals earlier in the day, may support energy metabolism and reduce the tendency toward excessive late-day energy intake. Early time-restricted feeding has been shown to improve certain metabolic parameters, including insulin sensitivity (Sutton et al., 2018).

2. Better Blood Glucose Regulation

Meal timing can influence glucose tolerance and insulin sensitivity. Consuming a greater proportion of food earlier in the day may support better blood glucose regulation and may contribute to reducing metabolic risk when combined with an overall healthy diet and lifestyle.

3. Improved Heart Health

Maintaining regular eating patterns and avoiding excessive late-night energy intake may contribute to better cardiometabolic health. Healthy meal timing should, however, be considered alongside other important factors such as physical activity, healthy food choices, adequate sleep, and maintaining a healthy body weight.

4. Better Digestion

The digestive system follows circadian patterns, and eating primarily during the active phase of the day may support normal digestive function. Avoiding heavy meals immediately before bedtime may help reduce problems such as discomfort, reflux, and indigestion in susceptible individuals.

5. Better Sleep

Late-night heavy meals and frequent nighttime snacking may interfere with comfortable sleep. Eating dinner earlier and allowing adequate time between dinner and bedtime may support better sleep quality as part of a healthy daily routine.

6. Improved Mental Performance

A balanced diet and regular meal schedule can help provide a steady supply of energy and essential nutrients required for normal brain function. A nutritious breakfast may be particularly useful for individuals who have demanding academic or occupational schedules.

7. Healthy Ageing

Maintaining regular eating patterns along with a balanced diet, physical activity, and adequate sleep may support healthy ageing. Appropriate synchronization between eating patterns and circadian rhythms may contribute to better metabolic regulation and overall well-being.

Practical Tips for Following Chrono Nutrition

Chrono nutrition does not require expensive foods, complicated diets, or specialized products. Some simple practices include:

- Start the day with a nutritious breakfast.
- Prefer nutrient-dense foods over highly processed foods.
- Consume the major proportion of daily food intake during the active part of the day.
- Keep lunch nutritious and adequately balanced.
- Eat dinner approximately 2–3 hours before bedtime.
- Avoid frequent late-night snacking.
- Limit sugary drinks and highly processed foods, particularly at night.
- Maintain relatively consistent meal timings.
- Drink adequate water throughout the day.
- Combine healthy meal timing with regular physical activity and adequate sleep.

These practices can be adapted according to age, occupation, culture, food availability, and individual nutritional requirements.

Conclusion

Good nutrition is not only about what we eat but also, to some extent, when we eat**.** The human body follows circadian rhythms that influence digestion, hormone secretion, glucose regulation, energy metabolism, and other physiological functions. Aligning meal timing with these natural rhythms may support metabolic health, digestion, healthy body weight, sleep, and overall well-being.

Chrono nutrition does not require expensive foods or complicated dietary plans. Simple practices such as having a nutritious breakfast, consuming adequate food during the active part of the day, maintaining regular meal timings, avoiding unnecessary late-night snacking, and having an early and relatively light dinner can contribute to healthier eating patterns.

As lifestyle-related diseases become increasingly common, paying attention to meal timing along with food quality, portion size, physical activity, and sleep provides a practical approach to promoting healthier living. These practices can be adapted for individuals of different age groups and living conditions, including rural communities, while taking individual nutritional needs into consideration.

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Role of Circular Bioeconomy in Sustainable Agriculture

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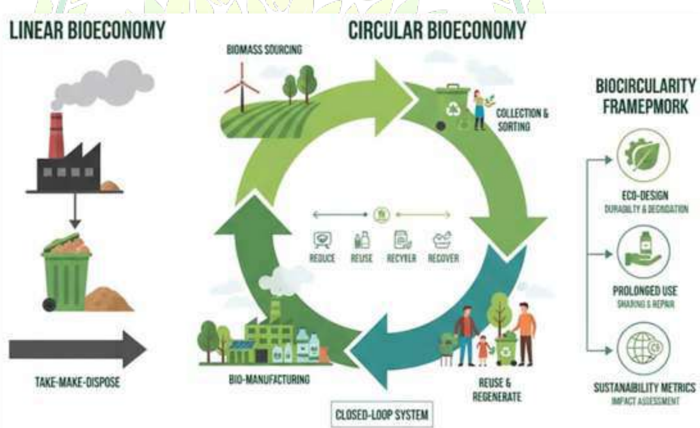
Agriculture is the fundamental source of food, livelihoods, and a wide range of bioresources. However, conventional agricultural production largely follows a linear "take–make–dispose" model. This linear approach is associated with the depletion of natural resources, soil degradation, accumulation of crop residues, livestock waste and food-processing by-products, as well as environmental problems such as pollution and greenhouse-gas emissions. Importantly, these materials contain stored carbon, nutrients, energy, and several valuable biochemical compounds that can potentially be recovered and reused. Therefore, agricultural wastes should be regarded as valuable secondary resources rather than merely as end products requiring disposal.



This is where the concept of the Circular Bioeconomy (CBE) becomes important. Circular bioeconomy combines the principles of the circular economy with the sustainable use of renewable biological resources to retain resources within productive systems for longer periods and minimize waste generation. The concept is based on the integration of two major ideas: biological resources and the circular economy**.** The bioeconomy promotes the use of renewable biological resources to produce food, feed, materials, chemicals, and energy, whereas the circular economy focuses on reducing resource losses and keeping materials and products in use for as long as possible. The integration of these concepts represents a transition from a conventional bioeconomy towards a circular bioeconomy.

In simple terms, circular bioeconomy can be defined as the application of circular economy principles to renewable biological resources**.** Its key objective is not only to use biomass for producing high-value products but also to utilize the remaining biomass fractions for animal feed, bioenergy generation, compost production, and nutrient recycling. Thus, circular bioeconomy is not simply about replacing fossil resources with biomass; rather, it emphasizes efficient resource utilization, environmental protection, resource recovery, and economic sustainability.

The circular bioeconomy approach follows the principles of reducing, reusing, recycling, and recovering resources. Biomass can be utilized in a stepwise or cascading manner, in which high-value products are recovered first, followed by lower-value applications such as animal feed, nutrient recycling, soil amendments, and energy generation. Incorporating this approach into agriculture can connect crop production, livestock farming, food processing, energy generation, and soil management within a closed-loop resource system.

Such circular systems provide environmental benefits while simultaneously creating new value chains and opportunities for rural income generation. However, their successful implementation depends on several factors, including technological availability, infrastructure, market conditions, economic feasibility, policy support, and management capacity. Despite these challenges, circular bioeconomy has considerable relevance to agriculture because biomass residues are continuously generated throughout the production, processing, and consumption chain.

Crop residues, animal manure, and food-processing by-products can be converted into biofertilizers, biogas, biofuels, biochar, biomaterials, and several other value-added products. Through these processes, nutrients, energy, and carbon can be recovered that would otherwise be lost. Recent developments in biotechnology, thermochemical processing, microbial conversion, and integrated biorefineries are further expanding the possibilities for biomass valorization.

Therefore, the transition from waste disposal towards resource recovery and biomass valorization can contribute significantly to the development of resource-efficient, climate-resilient, and economically sustainable agricultural systems.

Agricultural Biomass: From Residues to Resources

Agricultural production generates substantial quantities of crop residues, animal wastes, food-processing residues, and other forms of organic biomass. In conventional or poorly managed farming systems, a considerable proportion of these materials is treated as waste and is often burned, dumped, or left to decompose uncontrollably.

Practices such as open burning of crop residues and uncontrolled decomposition can contribute to air pollution, greenhouse-gas emissions, nutrient losses, and depletion of valuable organic matter. Therefore, agricultural residues should be considered secondary resources rather than merely waste materials.

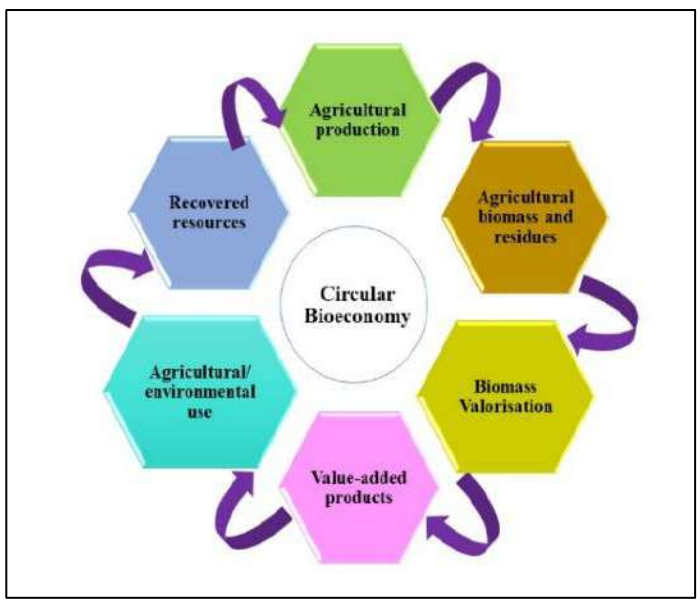


Figure 1. Agricultural circular bioeconomy pathway for biomass valorization

Major Sources of Agricultural Biomass

1. Crop Residues

Crop residues contain cellulose, hemicellulose, lignin, minerals, and other organic compounds. Major examples include straw, stalks, leaves, husks, cobs, shells, peels, and bagasse. Important agricultural residues include rice straw, wheat straw, maize stover, rice husk, and sugarcane bagasse.

These materials can be utilized for the production of bioenergy, compost, biochar, biochemicals, biomaterials, and other value-added products.

2. Livestock Production

Livestock farming generates substantial quantities of biomass in the form of cattle manure, poultry litter, pig manure, and other animal wastes. Improper management of livestock waste can cause unpleasant odors, greenhouse-gas emissions, and water contamination.

Circular approaches such as composting and anaerobic digestion can convert livestock waste into useful products while simultaneously generating renewable energy and returning nutrients to agricultural soils.

3. Horticultural and Food-Processing Residues

Horticultural and food-processing activities generate fruit and vegetable peels, seeds, shells, pomace, processing residues, and other organic by-products. These materials may contain carbohydrates, proteins, fibers, pigments, polyphenols, essential oils, and other valuable compounds.

Their diverse composition makes them suitable for animal feed, fermentation, bioenergy production, extraction of high-value compounds, and development of bio-based products. Thus, these materials can generate economic value that would otherwise be lost through conventional disposal.

Agricultural Residues as an Opportunity for Sustainable Agriculture

The transformation of agricultural residues into useful products can generate environmental, economic, and social benefits.

From an environmental perspective, biomass valorization can reduce resource depletion and uncontrolled waste disposal while facilitating the recovery of nutrients, organic carbon, and energy. It can also reduce dependence on fossil-derived resources.

From an economic perspective, biomass valorization can create new value chains associated with bioenergy, biofertilizers, biomaterials, bio-based chemicals, and other products. This can provide additional income opportunities for farmers, rural entrepreneurs, agro-industries, and local communities.

From a social perspective, decentralized biomass-processing facilities can generate employment and entrepreneurship opportunities in rural areas. The commercialization of agricultural by-products can also promote local enterprises, product branding, and rural economic development.

In developing countries such as India, crop-residue burning remains an important environmental concern. Several alternatives have been explored, including in-situ residue management, biogas production, biochar production, bioethanol production, composting, and vermicomposting (Rao et al., 2024).

Thus, the challenge is not simply to dispose of agricultural waste but to identify the most appropriate pathway for retaining its biological, environmental, and economic value within the production system. This concept forms the foundation of biomass valorization, which represents an important component of the circular bioeconomy.

Biomass Valorization Technologies: Converting Agricultural Waste into Value

Biomass valorization refers to the recovery and conversion of valuable components present in biomass into useful products, materials, nutrients, and energy after their primary use.

The mere availability of agricultural biomass does not guarantee successful circular resource utilization. Effective valorization requires suitable technologies capable of converting heterogeneous biomass into useful products in an economically and environmentally sustainable manner.

Table 1. Major biomass valorization techniques for converting agricultural waste into value-added products

Valorization pathway/approach	Main process	Major products	Contribution to circular bioeconomy
Composting	Microbial aerobic decomposition	Compost, organic matter, nutrients	Organic matter and nutrient recycling
Anaerobic digestion	Microbial conversion in the absence of oxygen	Biogas and digestate	Renewable energy generation and nutrient recovery
Fermentation and enzymatic conversion	Microbial/enzymatic bioconversion	Bioethanol, organic acids, enzymes, chemicals	Production of bio-based products
Pyrolysis	Thermal decomposition under limited oxygen	Biochar, bio-oil, and gases	Carbon retention and energy/material recovery
Gasification	High-temperature thermochemical conversion	Syngas	Production of heat, power, fuels, and chemicals
Hydrothermal conversion	Heat and pressure treatment of wet biomass	Hydrochar and bio-crude	Valorization of wet biomass without intensive drying
High-value compound extraction	Extraction and purification	Polyphenols, pigments, proteins, fibers, essential oils	Maximization of economic value before energy recovery
Biorefinery	Fractionation followed by multiple conversion pathways	Fuels, chemicals, materials, bioactive compounds	Multiproduct and cascading biomass utilization

Integrated valorization	Combination of biological and thermochemical processes	Multiple products	Minimization of residual waste and closure of resource loops

Applications of Biomass Valorization in the Circular Bioeconomy

Biomass valorization technologies can be applied across agricultural and agro-industrial systems to convert residues and by-products into value-added commodities. The selection of an appropriate pathway depends on biomass composition, resource availability, processing requirements, technological feasibility, economic considerations, and the desired end products.

Some representative applications of agricultural biomass valorization and their contributions to circular resource utilization are presented in Table 2.

Table 2. Applications of agricultural biomass valorization in a circular bioeconomy

Case study/application	Biomass/resource	Circular approach	Major product/output	Key significance
1. Crop-residue management in India	Rice and wheat residues	In-situ management, bioenergy, biochar, bioethanol, and vermicomposting	Soil amendments, energy, and biofuels	Reduces residue burning while recovering nutrient and energy value (Rao et al., 2024)
2. Decentralized food-waste anaerobic digestion in Singapore	Food waste from a hawker centre	Decentralized anaerobic digestion	Biogas (~56.9% CH_4) and digestate	Demonstrates real-world food-waste-to-energy conversion and nutrient recovery (Tiong et al., 2024)
3. Agro-industrial waste biorefinery	Sugarcane bagasse, rice husk, wheat straw, fruit residues, and other agro-industrial wastes	Integrated biochemical, enzymatic, and biorefinery processes	Biofuels, chemicals, biomaterials, and bioactive products	Enables cascading valorization of diverse biomass fractions (Wagh et al., 2024)
4. Food-waste digestate recovery	Anaerobic digestate from food waste	Bio-conditioning, dewatering, and biological treatment	Recovered nutrients and treated effluent	Converts digestate into a resource-recovery stream (Zhou et al., 2024)

5. Agricultural residues to biochar	Rice straw and other crop residues	Thermochemical conversion/pyrolysis	Biochar	Converts agricultural residues into carbon-rich soil amendments and supports resource recovery (Rao et al., 2024)

Challenges and Future Directions

Despite its considerable potential, the agricultural circular bioeconomy faces several challenges. Agricultural biomass is often available seasonally and may vary considerably in quality, composition, particle size, moisture content, and geographical distribution. Consequently, the collection, transportation, and storage of biomass can become expensive and technically challenging.

The establishment of processing facilities, including biorefineries, often requires substantial initial investment. In addition, inconsistent biomass quality, uncertain supply, fluctuating market demand, and inadequate infrastructure may affect economic viability and profit margins.

Technologies developed under laboratory conditions may also encounter difficulties during large-scale commercial implementation. Therefore, technological scalability, energy requirements, environmental impacts, product quality, and economic feasibility must be carefully evaluated before commercialization. Environmental safety is another critical consideration. Circularity should not be pursued at the expense of environmental sustainability. Appropriate management is required to prevent the accumulation of contaminants, pathogens, heavy metals, or other undesirable substances within circular resource systems.

Future efforts should focus on the selection of appropriate, locally adaptable, economically viable, and environmentally safe valorization technologies. Digital technologies and artificial intelligence can potentially support biomass characterization, resource mapping, technology selection, supply-chain optimization, process monitoring, and prediction of product quality.

Ultimately, the goal should be to develop closed-loop agricultural systems in which carbon, nutrients, water, energy, and biomass are continuously recovered and reused within agro-based production systems.

Conclusion

The circular bioeconomy provides a practical framework for transforming agricultural waste from an environmental burden into a source of products, energy, nutrients, materials, and economic value. By integrating biomass utilization, valorization technologies, and resource recovery, circular bioeconomy approaches can contribute substantially to sustainable agriculture while reducing dependence on finite resources.

However, successful implementation requires technologies that are economically viable, environmentally safe, technically feasible, and locally adaptable**.** Future efforts should therefore move beyond the conventional "waste-to-product" approach towards integrated, decentralized, multi-product, and resource-efficient systems.

The fundamental principle can be summarized as: "Agricultural waste is not the end of the production chain; rather, it is the beginning of an additional value chain."

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Hepatoprotective and Hepatocurative Plants of India: Nature's Green Support for a Healthy Liver

ARTICLE ID: 0411

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The human liver is one of the most remarkable organs of the body. It functions as a metabolic laboratory, processing nutrients, synthesizing essential proteins, storing energy, producing bile, and metabolizing potentially harmful substances. Its central role in metabolism and detoxification also makes it susceptible to considerable stress from continuous exposure to alcohol, certain medications, environmental toxins, infections, obesity, and unhealthy dietary patterns. India has a long and rich history of using medicinal plants to support liver health. Ayurveda, Siddha, and other traditional systems of medicine have identified several plants traditionally used for conditions associated with impaired liver function, jaundice, and digestive disorders. These plants have subsequently attracted scientific interest because of their potential hepatoprotective and hepatocurative activities. Important medicinal plants traditionally associated with liver health include Bhumyamalaki, Kutki, Kalmegh, Amla, Haldi, Daruharidra, and Yashtimadhu. However, evidence for these plants varies considerably, and many have been evaluated primarily through laboratory and preclinical studies, with relatively limited clinical evidence for specific liver diseases. Therefore, medicinal plants should be considered potential sources of supportive therapies and not substitutes for professional medical diagnosis and treatment.

India is a rich repository of medicinal plants, many of which contain biologically active compounds such as flavonoids, phenolics, terpenoids, alkaloids, lignans, tannins, and other antioxidant constituents. Scientific research suggests that some of these compounds may exert protective effects on liver cells by reducing oxidative stress, inflammation, lipid peroxidation, and cellular injury.

Several Indian medicinal plants have therefore attracted considerable attention for their potential hepatoprotective properties. Scientific investigations have attempted to understand their mechanisms of action, active constituents, standardization requirements, efficacy, and safety. However, the level of scientific evidence varies among species, plant parts, preparations, and liver conditions. Consequently, further pharmacological studies, standardized preparations, well-designed clinical trials, and systematic safety evaluations are required.

Among the medicinal plants traditionally recognized in India for their potential role in liver health are Bhumyamalaki, Kutki, Kalmegh, Amla, Haldi, Daruharidra, and Yashtimadhu.

1. Bhumyamalaki : *Phyllanthus niruri* L.

Family: Phyllanthaceae

Bhumyamalaki is a small herb widely distributed throughout tropical and subtropical regions of India. Traditionally, it has been used for ailments associated with the liver and urinary system. The plant contains several bioactive constituents, including lignans, flavonoids, phenolic compounds, and other phytochemicals.

Experimental studies have reported antioxidant, anti-inflammatory, and hepatoprotective properties of *Phyllanthus niruri*. Its traditional use in jaundice and liver-related disorders has attracted particular scientific interest. Human studies have also been conducted to investigate its potential effects on liver function and oxidative stress.

A randomized, double-blind, placebo-controlled study investigated *P. niruri* in patients with alcoholic hepatitis, evaluating liver and renal function indices as well as markers of oxidative stress. Such studies demonstrate the increasing scientific interest in this traditional medicinal plant. Nevertheless, available evidence should not be interpreted as support for self-treatment of alcoholic liver disease. Alcohol abstinence, appropriate medical management, and professional monitoring remain essential.

2. Kutki: *Picrorhiza kurroa* Royle ex Benth.

Family: Plantaginaceae

Kutki is an important medicinal plant traditionally associated with hepatobiliary disorders in Indian systems of medicine. It is a small perennial herb native to the Himalayan region and is particularly valued for its bitter rhizomes. The major marker compounds of *Picrorhiza kurroa* include picroside-I and picroside-II, which have been extensively investigated.

Experimental studies have demonstrated potential hepatoprotective activity of *P. kurroa*. Early clinical investigations have also examined its application in liver disorders. In a randomized, double-blind, placebo-controlled study, *P. kurroa* root powder was reported to improve bilirubin and serum transaminase parameters in patients with acute viral hepatitis compared with the placebo group.

An important aspect of such research is the standardization of the preparation based on its picroside content. This highlights a fundamental principle of herbal medicine: quality control and chemical standardization are essential for ensuring consistency and reproducibility.

Kutki therefore represents an important example of how traditional knowledge of Himalayan medicinal plants can contribute to modern pharmacological research. However, its therapeutic use should be based on appropriate evidence, standardized preparations, and professional guidance (Vaidya et al., 1996).

3. Kalmegh: *Andrographis paniculata* (Burm.f.) Nees

Family: Acanthaceae

Kalmegh is a strongly bitter herb widely used in India and several other Asian countries. Traditionally, it has been used for fever, digestive disorders, and liver-related conditions. Andrographolide is the major bioactive diterpenoid constituent of the plant and has been extensively investigated.

Research indicates that *A. paniculata* and andrographolide may influence inflammatory and oxidative pathways involved in liver injury. Experimental studies using *A. paniculata* extracts have reported hepatoprotective activity against chemically induced liver damage.

The anti-inflammatory mechanisms associated with andrographolide have also been investigated, with findings suggesting potential modulation of inflammatory signaling pathways. These observations make Kalmegh an important candidate for further investigation in hepatoprotection. However, experimental evidence should not be equated with established clinical efficacy for liver diseases (Chua, 2014).

4. Amla: *Phyllanthus emblica* L.

Family: Phyllanthaceae

Amla, commonly known as Indian gooseberry, is one of the most popular medicinal fruits in India. It is widely used in Ayurveda and is also consumed as a food. Its fruits contain vitamin C, polyphenols, tannins, flavonoids, and other phytochemical constituents.

The antioxidant activity of *P. emblica* is of particular interest in relation to liver protection because oxidative stress is an important mechanism involved in several forms of liver injury. Extracts and isolated constituents of *P. emblica* have been reported to possess antioxidant, anti-inflammatory, and hepatoprotective properties.

The dual role of Amla as both a food and a traditionally used medicinal plant makes it particularly interesting for nutritional and pharmacological research. Nevertheless, questions concerning mechanisms of action, extraction methods, quality control, dosage, and safety require further investigation before specific therapeutic claims can be established.

5. Haldi: *Curcuma longa* L.

Family: Zingiberaceae

Turmeric is an important component of Indian culinary and traditional medicinal practices. The rhizome of *Curcuma longa* has been used as a spice and in Ayurveda and household remedies for centuries. Curcumin, a yellow-colored polyphenolic compound, is the best-known bioactive constituent of turmeric.

Experimental research indicates that curcumin can modulate oxidative stress, inflammatory pathways, and cellular responses associated with liver injury. Consequently, turmeric and curcumin have attracted considerable scientific interest in relation to metabolic dysfunction-associated fatty liver disease and other hepatobiliary conditions.

However, research on turmeric also highlights an important limitation of phytomedicine: promising laboratory and preclinical findings do not necessarily translate into proven clinical efficacy. Differences in curcumin content, bioavailability, formulations, dosage, and study design can substantially influence outcomes. Therefore, further standardized clinical investigations are required.

6. Daruharidra: *Berberis aristata* DC.

Family: Berberidaceae

Daruharidra is an important medicinal plant of the Himalayan region. Its roots and stem bark contain the alkaloid berberine, which has attracted considerable pharmacological interest.

Traditionally, *Berberis aristata* has been used in Indian systems of medicine for a variety of ailments. Modern research has described antimicrobial, antioxidant, anti-inflammatory, metabolic, and potential hepatoprotective or anti-hepatotoxic properties associated with the plant and its constituents.

Because *B. aristata* naturally occurs in Himalayan ecosystems and is subject to increasing demand, sustainable harvesting and cultivation are important. Indiscriminate collection from the wild may adversely affect natural populations. Therefore, conservation, scientific cultivation, and commercial utilization should progress together (Potdar et al., 2012).

7. Yashtimadhu: *Glycyrrhiza glabra* L.

Family: Fabaceae

Yashtimadhu, commonly known as licorice, is another medicinal plant widely mentioned in traditional systems of medicine. Its underground parts contain glycyrrhizin and various flavonoids and other bioactive compounds.

Glycyrrhiza glabra has been investigated for its anti-inflammatory and potential hepatoprotective effects. Its phytoconstituents may influence inflammatory and oxidative pathways involved in cellular injury.

However, the assumption that natural products are always harmless should be avoided. Excessive or prolonged consumption of glycyrrhizin-containing products may cause adverse effects. Therefore, medicinal use should be undertaken cautiously, particularly in individuals taking other medications or those with pre-existing health conditions.

Potential Mechanisms of Hepatoprotection

The potential hepatoprotective effects of medicinal plants may involve several interconnected biological mechanisms.

1. Antioxidant Activity

The liver is continuously exposed to oxidative stress generated during normal metabolic processes, and oxidative stress may increase during disease or exposure to toxic substances. Polyphenols, flavonoids, tannins, and other phytochemicals may help counteract oxidative damage by scavenging reactive oxygen species and supporting endogenous antioxidant defense mechanisms.

2. Anti-inflammatory Effects

Persistent inflammation can contribute to progressive liver injury and fibrosis. Several phytochemicals, including andrographolide and curcumin, have been investigated for their ability to modulate inflammatory signaling pathways in experimental models.

3. Protection of Liver-Cell Membranes

Certain plant extracts have demonstrated the potential to preserve cellular membrane integrity during experimental liver injury. Maintenance of membrane stability may reduce leakage of intracellular enzymes such as alanine aminotransferase (ALT) and aspartate aminotransferase (AST) into the bloodstream.

4. Reduction of Lipid Peroxidation

Lipid peroxidation can damage hepatocyte membranes and contribute to cellular dysfunction. Antioxidant phytochemicals may reduce lipid oxidation and thereby potentially limit oxidative injury to liver cells.

5. Modulation of Detoxification and Metabolic Pathways

Some plant-derived compounds may influence hepatic enzymes and cellular pathways involved in xenobiotic metabolism, lipid metabolism, and cellular antioxidant defense. These mechanisms are an important area of ongoing pharmacological research.

Hepatoprotective versus Hepatocurative Activity

The terms hepatoprotective and hepatocurative are related but should not be considered synonymous.

Hepatoprotective activity generally refers to the ability of a substance or plant preparation to prevent or reduce liver injury. In experimental studies, animals may be exposed to a hepatotoxic substance, followed by administration of a plant extract. The potential protective effect is subsequently evaluated using biochemical, antioxidant, molecular, and histopathological parameters.

In contrast, hepatocurative activity generally refers to the potential ability of a substance to support recovery or restoration after liver injury has already occurred. The term is used more frequently in traditional and popular literature than in standardized modern pharmacological terminology.

Therefore, claims of hepatocurative activity should be interpreted cautiously, particularly when they are based primarily on traditional use or preclinical studies. Evidence of prevention of liver injury in an experimental model does not automatically demonstrate that the same plant can cure an established human liver disease.

From Field to Pharmacy: Opportunities for Farmers

Growing scientific interest in medicinal plants also provides opportunities for Indian agriculture. Wherever suitable agro-climatic conditions, reliable planting material, appropriate cultivation practices, and an assured market are available, crops such as Amla, Kalmegh, turmeric, licorice, and selected medicinal herbs can provide opportunities for diversification of farm enterprises.

However, the cultivation of medicinal plants should not focus solely on biomass production. The concentration and quality of bioactive compounds may vary considerably depending on several factors, including:

- Genotype and chemotype
- Soil and water resources
- Altitude and agro-climatic conditions
- Plant age
- Harvesting season

- Plant part used
- Drying conditions
- Storage conditions
- Extraction methods
- Processing techniques

Therefore, Good Agricultural and Collection Practices (GACP), correct botanical authentication, appropriate harvesting, post-harvest management, and quality testing should form an integral part of medicinal-plant production.

Scientific cultivation may also help reduce pressure on wild populations of Himalayan medicinal plants such as *Picrorhiza kurroa* and *Berberis aristata*. Thus, conservation and commercial utilization should go hand in hand to ensure long-term sustainability.

Conclusion

Bhumyamalaki, Kutki, Kalmegh, Amla, Haldi, Daruharidra, and Yashtimadhu represent only a small selection of India's vast medicinal-plant heritage. Scientific research has provided evidence for several potentially hepatoprotective mechanisms, including antioxidant, anti-inflammatory, membrane-stabilizing, and lipid-peroxidation-reducing activities. Some plants have also progressed from traditional use to experimental and early clinical investigations.

However, the strength of evidence is not uniform across species, preparations, doses, or liver diseases. Consequently, medicinal plants should be viewed as promising sources of supportive or complementary interventions rather than universal cures for liver disorders.

A healthy liver also depends on balanced nutrition, regular physical activity, avoidance of excessive alcohol consumption, responsible use of medications, maintenance of a healthy body weight, and appropriate medical evaluation when symptoms or risk factors are present.

India's medicinal-plant heritage represents an invaluable biological and cultural resource. Through scientific cultivation, botanical authentication, sustainable harvesting, chemical standardization, rigorous pharmacological investigation, and well-designed clinical studies, these “green medicines” may contribute meaningfully to future research on liver health while simultaneously supporting sustainable agricultural development.

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Sterility Mosaic Disease: A Silent Threat to Pigeonpea and the Search for Resistant Varieties

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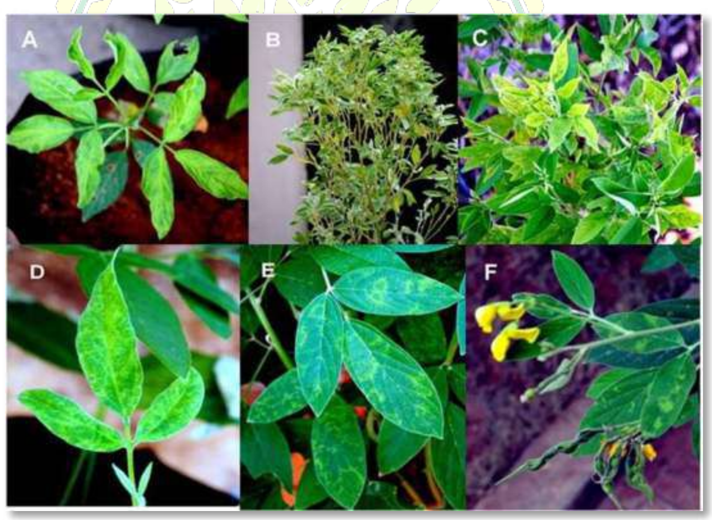
Pigeonpea [*Cajanus cajan* (L.) Millsp.] is an important pulse crop that contributes significantly to food security and farmers' livelihoods. However, its productivity is severely affected by sterility mosaic disease (SMD), one of the most destructive viral diseases of pigeonpea. Commonly known as the "Green Plague", SMD is caused by *Pigeonpea sterility mosaic virus-1* (PPSMV-1) and *Pigeonpea sterility mosaic virus-2* (PPSMV-2), transmitted by the eriophyid mite *Aceria cajani*. Owing to the absence of an effective curative treatment, the development of resistant varieties remains the most reliable and economical strategy for disease management. This article highlights the importance of pigeonpea, major features of SMD, challenges associated with its management, and the role of conventional and molecular breeding approaches in developing resistant cultivars.



Pigeonpea [*Cajanus cajan* (L.) Millsp.] is one of the most important pulse crops cultivated in tropical and subtropical regions worldwide, particularly in India. Commonly known as tur, red gram or arhar, pigeonpea plays a significant role in the livelihoods of resource-poor farmers because of its relatively low input requirements. It is a highly valued multipurpose food legume. Its protein-rich seeds are widely consumed, while immature green pods are utilized as vegetables. The foliage serves as livestock fodder, whereas dried stems are used as fuel and thatching material.

From a nutritional standpoint, pigeonpea is a rich source of essential minerals such as calcium, phosphorus, magnesium, iron, sulphur and potassium, along with water-soluble vitamins including thiamine, riboflavin and niacin. The seeds contain approximately 20–22% protein and are consumed in various forms, including green peas, whole grains and split pulses. Besides its nutritional importance, pigeonpea contributes to sustainable agriculture through biological nitrogen fixation, improvement of soil fertility and adaptation to rainfed conditions.

Despite its importance, pigeonpea productivity remains considerably below its potential because of several biotic and abiotic constraints, among which diseases pose a major challenge.

Among these diseases, sterility mosaic disease (SMD), often referred to as the "Green Plague" of pigeonpea, is considered one of the most destructive. Unlike many plant diseases that primarily affect leaves or stems, SMD severely affects the reproductive development of the crop. Infected plants remain green and exhibit excessive vegetative growth, but flowering is greatly reduced or completely absent, resulting in little or no pod formation. Consequently, severe infection can cause substantial yield losses and significant economic hardship for farmers.

The disease is caused by *Pigeonpea sterility mosaic virus* (PPSMV-1 and PPSMV-2) and is transmitted by the eriophyid mite *Aceria cajani*. The microscopic size of the vector, coupled with the complex nature of virus transmission, makes effective disease management extremely challenging. Chemical control of viral diseases is generally ineffective, while management of the mite alone seldom provides complete protection against the disease. Consequently, sterility mosaic disease continues to threaten pigeonpea production across major growing regions.

Over the past few decades, considerable research has focused on understanding the disease, identifying resistant sources and developing improved pigeonpea cultivars capable of withstanding infection. Conventional breeding, supported by molecular markers and modern genomic tools, has accelerated the development of resistant varieties and offers one of the most sustainable approaches to disease management. Such advances not only reduce dependence on pesticides but also contribute to stable yields and improved food security.

This article explores the biology and impact of sterility mosaic disease, discusses the factors that make the disease difficult to manage, and highlights scientific efforts aimed at developing disease-resistant pigeonpea varieties for sustainable agriculture.

The Silent Threat: Sterility Mosaic Disease

Sterility mosaic disease (SMD) was first reported by Mitra in 1931 from Bihar, India. Since then, it has emerged as one of the most destructive diseases of pigeonpea in the Indian subcontinent, causing substantial economic losses. The disease is endemic to India and has also been reported from Bangladesh, Nepal, Myanmar, Sri Lanka, Thailand and China. In India, SMD occurs in almost all major pigeonpea-growing states, including Andhra Pradesh, Bihar, Chhattisgarh, Gujarat, Karnataka, Maharashtra, Punjab, Tamil Nadu, Telangana, Uttar Pradesh and West Bengal.

The characteristic symptoms of SMD include mosaic patterns, bushy and pale-green plants with excessive vegetative growth, smaller leaves, stunting, leaf distortion and reduced flowering or complete cessation of flowering. Infected plants may also exhibit reduced plant height, fewer branches, fewer flowers and shorter pods.

The term "Green Plague" reflects the striking appearance of infected plants. Although the plants remain green and continue producing vegetative growth, they fail to produce normal flowers and pods. The severity of symptoms depends largely on the pigeonpea genotype and the stage of infection.

In susceptible plants infected at an early stage, particularly before approximately 45 days after sowing, symptoms are generally severe and flowering may cease completely, resulting in complete sterility. Infections occurring at later stages tend to produce milder symptoms, including mosaic symptoms on only a few branches, reduced flowering and partial sterility. Based on symptom expression, SMD symptoms can broadly be categorized into three types:

1. Severe mosaic with complete sterility
2. Mild mosaic with partial sterility
3. Chlorotic ring spots without sterility

The disease can spread rapidly under favourable environmental conditions, making early detection and timely management essential.

The Culprit Behind the Disease

For several decades after sterility mosaic disease was first reported in 1931, its exact causal agent remained uncertain. A major breakthrough came with the identification of *Pigeonpea sterility mosaic virus* (PPSMV) as the causal agent. Subsequent molecular studies revealed that SMD is associated with two distinct viruses, namely *Pigeonpea sterility mosaic virus-1* (PPSMV-1) and *Pigeonpea sterility mosaic virus-2* (PPSMV-2), both belonging to the genus *Emaravirus*.

Field observations and molecular investigations have indicated differences in symptom expression associated with the two viruses. PPSMV-1 is mainly associated with chlorotic ring spots and line patterns, whereas PPSMV-2 is associated with mosaic symptoms, stunting and sterility. Mixed infections involving both viruses can result in more severe disease symptoms under field conditions.

Unlike many plant viruses that are transmitted by insects such as aphids or whiteflies, PPSMVs are transmitted by the microscopic eriophyid mite *Aceria cajani*. The mite has a relatively narrow host range and is primarily associated with pigeonpea and certain wild relatives. It is the principal known vector responsible for the transmission of SMD.

During feeding, the mite acquires the virus from infected plants and subsequently transmits it to healthy plants, thereby facilitating disease spread within and between fields.

Why Is SMD Difficult to Manage?

1. Efficient Vector-Mediated Spread

The disease is transmitted by the microscopic eriophyid mite *Aceria cajani*. Because of their extremely small size, these mites can remain unnoticed during field scouting and may be disseminated to nearby plants and fields, facilitating rapid disease spread.

2. Carryover Through Volunteer and Ratoon Plants

The virus-vector system depends on living host plants for survival and multiplication. Volunteer pigeonpea plants, ratoon crops and susceptible wild relatives may act as sources of inoculum and vector populations during the off-season. Their presence can make it difficult to break the disease cycle.

3. Protected Microhabitats on the Plant

The eriophyid mites can survive in protected microhabitats, including areas associated with leaf trichomes and young plant tissues. Their microscopic size and protected location make complete exposure to acaricide sprays difficult.

4. Lack of a Direct Curative Treatment

Once a plant becomes infected, there is no effective chemical treatment capable of eliminating the virus from the plant. Management therefore primarily focuses on reducing vector populations, removing sources of inoculum and preventing further disease spread.

5. Delayed Recognition of Symptoms

Early symptoms may be inconspicuous and can easily be overlooked during routine field observations. By the time characteristic symptoms such as excessive branching, mosaic patterns and cessation of flowering become prominent, the infection may already be well established and may have spread to neighbouring plants.

Management Strategies

Although no curative treatment is available for plants already infected with sterility mosaic disease, an integrated disease management approach can help reduce disease incidence and delay its spread.

Chemical Management

Acaricides can be used to suppress populations of the eriophyid mite *Aceria cajani*, thereby reducing the transmission of PPSMVs. However, repeated chemical applications may increase production costs and are often impractical for resource-poor farmers, particularly because pigeonpea is predominantly cultivated under low-input production systems.

Therefore, acaricides should be used judiciously and as a component of an integrated disease management programme rather than as a stand-alone solution.

Cultural Practices

Removal of volunteer pigeonpea plants, ratoon crops and susceptible wild hosts before sowing can help eliminate potential sources of virus inoculum and vector populations. Regular field sanitation and removal of severely infected plants may further reduce disease spread.

Agronomic Practices

Agronomic practices such as modification of sowing dates, plant density, spacing, intercropping and the use of border crops have been investigated for their potential to reduce SMD incidence. However, their effectiveness may vary with location, genotype, environmental conditions and vector pressure. Consequently, these practices alone cannot provide reliable disease control.

Limitations of Existing Management Practices

Despite their potential benefits, cultural and chemical management practices face several limitations, including labour requirements, additional production costs, limited availability of inputs and difficulties in achieving timely implementation.

Therefore, the cultivation of resistant varieties remains the most reliable, economical and environmentally sustainable strategy for the long-term management of sterility mosaic disease in pigeonpea.

The Search for Resistant Varieties

Breeding for disease-resistant varieties is considered one of the most effective and economical approaches for reducing crop losses and has received high priority in pigeonpea improvement programmes.

The search for resistance begins with germplasm screening, in which large numbers of pigeonpea lines—including cultivated varieties, breeding materials, landraces and wild relatives—are evaluated under natural or artificial disease pressure. Such extensive screening has resulted in the identification of several resistant sources that serve as valuable donors in breeding programmes.

These resistant donor lines are crossed with high-yielding but susceptible cultivars to combine disease resistance with desirable agronomic traits such as high yield, early maturity and good grain quality. The resulting progenies are evaluated over successive generations to identify plants that combine stable resistance with superior agronomic performance.

Traditionally, resistance has been assessed through field screening, in which breeding populations are exposed to disease pressure through the mite vector. Genotypes that remain free from disease symptoms are subsequently evaluated to confirm the stability and nature of their resistance.

Although conventional screening methods are effective, they are labour-intensive and time-consuming. Their effectiveness may also depend on environmental conditions, vector abundance and the availability of virulent virus isolates.

Role of Molecular Breeding in SMD Resistance

The identification of molecular markers associated with SMD resistance has significantly improved the efficiency of resistance breeding. Molecular markers enable breeders to identify plants carrying resistance-associated genomic regions at an early stage, without waiting for disease symptoms to develop.

This approach can reduce the time, labour and resources required for repeated field evaluations. Once validated, molecular markers can be incorporated into marker-assisted selection (MAS) programmes, allowing breeders to select desirable plants at early generations.

The integration of conventional breeding with marker-assisted selection has accelerated the development of SMD-resistant pigeonpea cultivars. Molecular breeding can also facilitate the identification and utilization of diverse resistance sources and support the development of cultivars with broader and more stable resistance.

Improved cultivars must subsequently be evaluated across multiple locations and growing seasons to determine the stability of resistance under diverse environmental conditions and disease pressures.

The development and adoption of SMD-resistant varieties can substantially reduce yield losses and provide farmers with a sustainable and cost-effective approach to disease management.

Future Prospects

Future research on sterility mosaic disease should focus on identifying diverse and durable sources of resistance, understanding the molecular mechanisms underlying host resistance, and developing reliable molecular markers for efficient selection.

Advances in genomics, transcriptomics, marker-assisted selection, genomic selection and other molecular breeding approaches offer significant opportunities for accelerating the development of resistant pigeonpea cultivars.

Greater emphasis should also be placed on understanding the interactions among pigeonpea genotypes, PPSMV-1, PPSMV-2 and *Aceria cajani*. Such knowledge will be valuable for developing integrated disease management strategies and identifying resistance that remains effective against diverse virus populations and vector pressures.

The combination of resistant cultivars with appropriate cultural practices and judicious vector management is likely to provide the most sustainable strategy for minimizing the impact of SMD.

Conclusion

Sterility mosaic disease continues to pose a major challenge to sustainable pigeonpea production because of its widespread occurrence, complex virus-vector relationship and the absence of effective curative control measures. The identification of *Pigeonpea sterility mosaic virus-1* and *Pigeonpea sterility mosaic virus-2*, together with improved understanding of their transmission by the eriophyid mite *Aceria cajani*, has significantly advanced research on this disease.

Although cultural practices and vector management can help reduce disease incidence under certain conditions, the development and deployment of resistant varieties remain the most practical, economical and environmentally sustainable strategy for long-term management.

Advances in conventional breeding, supported by molecular markers and other genomic tools, have accelerated the identification and incorporation of resistance into improved pigeonpea cultivars. Continued efforts in resistance breeding, integrated disease management and the application of modern molecular technologies will be essential to minimize yield losses and ensure sustainable pigeonpea production for future generations.

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Colostrum to Mature Milk: Mineral and Vitamin Dynamics Across Buffalo Breeds — A Review

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Buffalo (*Bubalus bubalis*) colostrum undergoes rapid and measurable biochemical changes during the first two weeks after calving, with the most pronounced shifts occurring within the first 48–120 hours postpartum. This review compiles quantitative data from peer-reviewed studies on Egyptian, Murrah, Kundi, Nili-Ravi, Jaffarabadi, Surti, and Mediterranean buffaloes to document changes in macro-minerals (Ca, Mg, Na, K, and P), micro-minerals (Fe, Cu, Zn, and Pb), fat-soluble vitamins (A and E), and key bioactive components, including immunoglobulins, insulin-like growth factor-1 (IGF-1), and lactoferrin, from calving through the transition to mature milk. Breed-wise numerical comparisons are presented to highlight genetic variation superimposed on the universal effect of lactation stage. The compiled data provide specific reference values that may be useful to students, dairy technologists, veterinarians, and researchers requiring quantitative information on buffalo colostrum composition rather than qualitative descriptions of general trends alone.

Colostrum represents the first mammary secretion produced after parturition and is compositionally distinct from mature milk. In buffaloes, the transition from colostrum to mature milk is rapid and measurable within hours after calving. Several macro- and micro-elements decline substantially during the first few days postpartum, whereas lactose and other components generally change in the opposite direction.

This review synthesizes quantitative information reported in peer-reviewed studies on Egyptian buffaloes (Abd El-Fattah et al., 2012), Murrah buffaloes (Dang et al., 2009), Kundi and Nili-Ravi buffaloes (Ahmad et al., 2024), and comparative buffalo-breed studies involving Murrah, Nili-Ravi, Jaffarabadi, and Mediterranean buffaloes. Particular emphasis is placed on numerical changes in minerals, vitamins, immunoglobulins, and other bioactive components during the transition from colostrum to mature milk.

The objective is to provide a consolidated quantitative reference that illustrates both the universal changes associated with lactation stage and the breed-specific differences reported among buffalo populations.

Macro-Mineral Changes: Calcium, Magnesium, Sodium, Potassium and Phosphorus

The following table presents mean concentrations of selected macro-minerals reported in Egyptian buffalo colostrum from the time of calving through Day 14, when the composition approaches that of mature milk.

Table 1. Changes in macro-mineral concentration in Egyptian buffalo colostrum during the transition to mature milk

Time postpartum	Ca (mg/100 g)	Mg (mg/100 g)	Na (mg/100 g)	K (mg/100 g)	P (mg/100 g)
At calving (0 h)	279.60	35.52	150.50	107.00	58.00
6 h	273.20	33.34	128.80	105.30	56.00
12 h	270.60	29.60	105.80	101.30	54.00
24 h (Day 1)	261.80	29.20	81.90	102.20	53.00
48 h (Day 2)	239.80	25.10	76.56	100.10	52.00
72 h (Day 3)	190.90	24.12	56.04	89.20	52.00
96 h (Day 4)	160.10	19.90	63.28	82.63	54.00
120 h (Day 5)	140.20	17.50	36.44	79.80	52.00
Day 14 (mature)	114.00	13.46	38.20	74.00	57.00

Source: *Abd El-Fattah et al. (2012),* BMC Veterinary Research*, 8:19. Values are means (mg/100 g).*

Calcium decreased from 279.60 mg/100 g at calving to 114.00 mg/100 g by Day 14, representing a decline of approximately 59%. Magnesium decreased from 35.52 to 13.46 mg/100 g, corresponding to approximately a 62% decline. Sodium showed the steepest decline among the macro-minerals, decreasing from 150.50 to 38.20 mg/100 g, equivalent to approximately a 75% reduction over the two-week period.

Potassium declined more gradually, from 107.00 to 74.00 mg/100 g. In contrast, phosphorus remained comparatively stable, changing from 58.00 to 57.00 mg/100 g during the same period. Thus, phosphorus was the most stable macro-mineral in this dataset.

Micro-Mineral Changes: Iron, Copper, Zinc and Lead

Micro-minerals also exhibited substantial changes during the transition from colostrum to mature milk, with iron and copper showing particularly pronounced reductions.

Table 2. Changes in micro-mineral concentration in Egyptian buffalo colostrum

Time postpartum	Fe (mg/100 g)	Cu (mg/100 g)	Zn (mg/100 g)	Pb (mg/100 g)
At calving (0 h)	2.36	0.186	0.23	0.028
6 h	1.50	0.118	0.21	0.024
12 h	0.77	0.084	0.21	0.020
24 h	0.76	0.082	0.20	0.018
48 h	0.66	0.077	0.17	0.018
72 h	0.60	0.060	0.15	0.012
96 h	0.51	0.060	0.13	0.010
120 h (Day 5)	0.54	0.052	0.12	0.010
Day 14 (mature)	0.53	0.020	0.16	0.009

Source: *Abd El-Fattah et al. (2012),* BMC Veterinary Research*, 8:19. Values are means (mg/100 g).*

Iron concentration decreased from 2.36 mg/100 g at calving to 0.53 mg/100 g by Day 14, representing an approximate 78% decline. Most of this reduction occurred within the first 12 hours, when iron decreased from 2.36 to 0.77 mg/100 g.

Copper showed an even greater reduction, decreasing from 0.186 to 0.020 mg/100 g, corresponding to an approximate 89% reduction. In this dataset, copper therefore exhibited the most pronounced decline among the measured trace minerals.

Zinc decreased more moderately, from 0.23 mg/100 g at calving to 0.16 mg/100 g by Day 14. Lead decreased from 0.028 to 0.009 mg/100 g over the same period.

Vitamin A and Vitamin E Dynamics

Unlike several minerals, vitamin concentrations in buffalo colostrum did not demonstrate a simple linear decline. Both vitamin A and vitamin E exhibited fluctuations during the early postpartum period before approaching levels associated with mature milk.

Table 3. Changes in vitamin A and vitamin E concentrations in Egyptian buffalo colostrum

Time postpartum	Vitamin A (IU/100 ml)	Vitamin E (IU/100 ml)
At calving (0 h)	166.67	342.00
6 h	125.00	402.00

12 h	145.83	336.00
24 h	188.03	396.00
48 h	171.90	387.00
72 h	156.25	378.00
96 h	146.20	352.97
120 h (Day 5)	138.20	341.67
Day 14 (mature)	136.70	330.00

Source: *Abd El-Fattah et al. (2012),* BMC Veterinary Research*, 8:19. Values are expressed as IU/100 ml.*

Vitamin E reached a maximum concentration of 402.00 IU/100 ml at 6 hours postpartum, compared with 342.00 IU/100 ml at calving, before gradually decreasing to 330.00 IU/100 ml by Day 14. Relative to the initial calving value, this represents an overall decline of approximately 3.5%, making vitamin E the more stable of the two fat-soluble vitamins evaluated.

Vitamin A followed a less consistent pattern. Its concentration decreased from 166.67 IU/100 ml at calving to 125.00 IU/100 ml at 6 hours, subsequently increased to 188.03 IU/100 ml at 24 hours, and then gradually decreased to 136.70 IU/100 ml by Day 14. This represents a net decline of approximately 18% relative to the initial calving value.

The same study reported that buffalo colostrum contained approximately 1.5 times less vitamin A than cow colostrum at calving, whereas vitamin E concentrations in buffalo colostrum remained consistently higher than those in cow colostrum throughout the study period.

Bioactive Components: Immunoglobulins, IGF-1 and Lactoferrin

In addition to minerals and vitamins, colostrum contains high concentrations of biologically active components that contribute to neonatal protection, development, and immune function. These include immunoglobulins, insulin-like growth factor-1 (IGF-1), and lactoferrin.

Table 4. Changes in selected bioactive components of Egyptian buffalo colostrum

Time postpartum	**IgG (mg/ml)**	**IgM (mg/ml)**	**IGF-1 (ng/ml)**	**Lactoferrin (mg/ml)**
At calving (0 h)	33.20	3.00	801.90	1.085
Day 5 (120 h)	~2% of initial	Declined sharply	~181 (77.4% decrease)	Declined sharply
Day 14 (mature)	Near-baseline	Near-baseline	Near-baseline	0.123

Source: *Abd El-Fattah et al. (2012),* BMC Veterinary Research*, 8:19.*

IgG and IgM decreased by approximately 97.9% and 97.5%, respectively, within the first five days postpartum. IGF-1 decreased from 801.90 ng/ml at calving to approximately 181 ng/ml by Day 5, representing a 77.44% reduction. Lactoferrin also declined substantially, from 1.085 mg/ml at calving to 0.123 mg/ml by Day 14.

Immunoglobulin Changes in Murrah Buffaloes

Dang et al. (2009) investigated changes in colostrum composition in Murrah buffaloes following calving. The study reported an average IgG concentration of 54.0 mg/ml at calving, together with IgA at 3.22 mg/ml and IgM at 5.22 mg/ml on Day 1. These immunoglobulin concentrations were reported to be higher than corresponding values in cows. Somatic cell count (SCC) was elevated at calving, reaching approximately 500,000 cells/ml, and decreased to 180,000 cells/ml by Day 5. Phagocytic activity was reported to peak on Day 1, further emphasizing the biological importance of early colostrum intake.

Table 5. Changes in immunoglobulins and somatic cell count in Murrah buffalo colostrum

Day after calving	IgG (mg/ml)	IgA (mg/ml)	IgM (mg/ml)	SCC (per ml)
Day 1	54.0 (average at calving)	3.22	5.22	500,000
Day 2	Declining	Declining	Declining	Reduced significantly
Day 5	Significantly lower	Lower	Lower	180,000

Source: *Dang et al. (2009),* Tropical Animal Health and Production*, 41(7):1213–1217.*

The rapid decline in immunoglobulins after calving reinforces the importance of timely colostrum administration to newborn buffalo calves.

Breed-Wise Numerical Comparison

Buffalo breeds differ in their milk-production characteristics and in the concentration of individual milk components. The available literature demonstrates that breed effects may occur alongside the strong effect of lactation stage.

Kundi versus Nili-Ravi Buffalo Colostrum at 6 Hours Post-Calving

Ahmad et al. (2024) compared the physicochemical and antimicrobial characteristics of colostrum and milk from Kundi and Nili-Ravi buffaloes at different stages following calving. At 6 hours postpartum, clear differences were observed between the two breeds.

Table 6. Physicochemical characteristics of Kundi and Nili-Ravi buffalo colostrum at 6 hours postpartum

Parameter	Kundi Buffalo	Nili-Ravi Buffalo
Fat (%)	8.40 ± 0.06	6.00 ± 0.06
Protein (%)	13.82 ± 0.33	12.34 ± 0.72
Lactose (%)	2.72 ± 0.14	2.25 ± 0.01
SNF (%)	20.07 ± 0.01	19.79 ± 0.01
Total solids (%)	28.91 ± 0.01	25.98 ± 0.01
Ash (%)	1.04 ± 0.10	0.98 ± 0.04
pH	6.07 ± 0.00	6.37 ± 0.01
Viscosity	6.98 ± 0.01	7.33 ± 0.01

Source: Ahmad et al. (2024), *Journal of Population Therapeutics and Clinical Pharmacology*, 31(1):1264–1276.

Kundi buffalo colostrum contained higher fat (8.40% vs. 6.00%), protein (13.82% vs. 12.34%), and total solids (28.91% vs. 25.98%) than Nili-Ravi colostrum at the same 6-hour postpartum time point. In contrast, Nili-Ravi colostrum exhibited marginally higher viscosity and pH. These findings indicate the presence of breed-specific physicochemical signatures even within a relatively narrow postpartum period.

Murrah, Nili-Ravi, Jaffarabadi, Surti and Mediterranean Buffaloes: Mature Milk Characteristics

Data from comparative breed studies provide further evidence of variation in mature milk composition among buffalo breeds.

Table 7. Comparative mature milk characteristics among selected buffalo breeds

Breed	Fat (%)	Protein (%)	SNF (%)	Distinctive feature
Murrah	8.02 (reported maximum among breeds compared)	Higher than Nili-Ravi	9.41 (highest reported)	Highest whey protein and unsaturated fatty acids
Nili-Ravi	Lower than Murrah	Lower than Murrah	Lower than Murrah	Highest saturated fatty acids and casein fractions
Mediterranean (Italy)	Highest among Murrah, Nili-Ravi and Mediterranean trial	Highest among the three	Not separately reported	Highest cholesterol, sphingomyelin and lanosterol

Sources: *Zhou et al. (2018); Abdel-Hamid et al. (2023).*

A comparative study conducted in China on Murrah and Nili-Ravi buffalo milk reported significantly higher protein and total solids in Murrah buffalo milk than in Nili-Ravi milk. Across all buffalo samples, the average protein, fat, lactose, and total solids contents were 4.76%, 7.31%, 5.19%, and 18.40%, respectively. Amino acid analysis in the same study showed that Murrah milk had significantly higher concentrations of lysine, isoleucine, leucine, phenylalanine, cysteine, and histidine than Nili-Ravi milk.

In a separate three-breed comparison involving Murrah, Nili-Ravi, and Mediterranean buffaloes under identical housing and feeding conditions in China, Mediterranean buffalo milk had significantly higher fat and protein contents and the highest concentrations of sphingomyelin, cholesterol, and lanosterol. Murrah buffalo milk was distinguished by higher whey protein and total unsaturated fatty acid content, whereas Nili-Ravi milk exhibited higher total saturated fatty acids and specific casein fractions.

Jaffarabadi Buffalo Milk Composition Across Lactation Stages

Garaniya et al. (2013) evaluated the nutrient profile of Jaffarabadi buffalo milk across nine successive stages of lactation. Unlike breed-to-breed comparisons, this study primarily demonstrates the effect of lactation stage within a single breed.

Table 8. Changes in Jaffarabadi buffalo milk composition across nine lactation stages

Parameter	Trend across lactation stages (1–9)	Significant variation?
Fat (%)	Increased progressively as lactation advanced	Yes
pH, Protein, Density, SNF, Lactose	Remained largely stable	No
Iron, Copper (trace elements)	Remained nearly constant	No
Zinc, Manganese, Sodium	Varied significantly across stages	Yes
Potassium, Calcium (macro-elements)	Remained nearly constant	No

Source: *Garaniya et al. (2013),* Asian Journal of Dairy and Food Research, *32(2):168–170.*

Among the minerals evaluated, iron, copper, potassium, and calcium remained nearly constant across the nine lactation stages, whereas zinc, manganese, and sodium demonstrated significant stage-wise variation. These observations represent a within-breed lactation-stage effect rather than a direct comparison with another buffalo breed.

Consolidated Observations

The quantitative evidence reviewed in this article highlights several major patterns in the transition from buffalo colostrum to mature milk:

- Sodium showed the steepest macro-mineral decline, decreasing by approximately 75% from calving to Day 14.
- Copper showed the greatest decline among the measured micro-minerals, decreasing by approximately 89%, followed by iron at approximately 78%.
- Phosphorus was the most stable macro-mineral, changing by less than 2% between calving and Day 14.
- Vitamin E was more stable than vitamin A during the transition. Buffalo colostrum contained higher vitamin E but lower vitamin A concentrations than cow colostrum in the study considered.
- IgG and IgM decreased by more than 97% within five days, demonstrating the importance of early colostrum feeding for neonatal immune protection.
- Breed differences were measurable even at narrowly matched postpartum stages. Kundi buffalo colostrum showed higher fat, protein, and total solids than Nili-Ravi buffalo colostrum at 6 hours postpartum.

- Murrah buffaloes showed higher protein and total solids than Nili-Ravi buffaloes in the comparative studies considered, whereas Mediterranean buffaloes showed higher fat and specific lipid fractions.
- Jaffarabadi buffalo milk exhibited stage-dependent changes in fat and selected minerals, demonstrating that lactation stage can influence milk composition independently of breed effects.

Practical Implications

The quantitative changes documented in buffalo colostrum have important implications for calf management, dairy technology, and research.

For neonatal management, colostrum should ideally be provided to newborn calves as early as possible after birth. The rapid reduction in immunoglobulins during the first several days postpartum highlights the importance of timely colostrum intake, particularly during the first hours of life.

Breed-specific differences may also have implications for colostrum management. Kundi buffalo colostrum, for example, demonstrated higher fat, protein, and total solids than Nili-Ravi colostrum at 6 hours postpartum, whereas Jaffarabadi buffalo milk exhibited distinctive lactation-stage patterns. Such differences may need to be considered when developing breed-specific colostrum pooling, storage, or processing protocols.

From a dairy-processing perspective, relatively stable components such as phosphorus and vitamin E may be less sensitive indicators of the transition from colostrum to mature milk. In contrast, rapidly changing components such as sodium, copper, and immunoglobulins may provide more sensitive indicators of the stage of lactation and the progression from colostral to mature milk.

These observations may also be useful when designing future studies examining breed-specific milk composition, calf nutrition, colostrum quality, and the functional properties of buffalo milk.

Conclusion

The quantitative evidence reviewed from Egyptian, Murrah, Kundi, Nili-Ravi, Jaffarabadi, and Mediterranean buffalo studies demonstrates that the transition from colostrum to mature milk is rapid, measurable, and influenced by both lactation stage and breed.

Among the minerals evaluated, sodium and copper showed particularly pronounced declines, whereas phosphorus remained comparatively stable. Vitamin E exhibited greater stability than vitamin A. The most dramatic changes were observed among the immunological components, with IgG and IgM declining by more than 97% within the first five days postpartum.

Breed differences were also evident. Kundi buffaloes exhibited higher fat, protein, and total solids in colostrum than Nili-Ravi buffaloes at 6 hours postpartum. Murrah buffaloes demonstrated higher protein and total solids than Nili-Ravi buffaloes in comparative studies, while Mediterranean buffaloes exhibited higher fat and specific lipid fractions under the conditions reported. Jaffarabadi buffaloes demonstrated additional variation associated with lactation stage.

Overall, these quantitative data provide a useful reference framework for understanding the dynamic biochemical transition from buffalo colostrum to mature milk. The numerical values may assist researchers, students, veterinarians, dairy technologists, and animal scientists in designing further breed-specific and lactation-stage-specific investigations.

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