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THE ROLE OF COMPOST IN SUSTAINABLE WASTE MANAGEMENT: A COMPREHENSIVE REVIEW IN THE CONTEXT OF PAKISTAN

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Abstract

Composting, a method of solid waste management, involves the decomposition of organic waste and is a more sustainable alternative to landfills and incineration. Unlike these methods, which release harmful gases like CO₂ and methane, contributing to the greenhouse effect, and potentially spreading diseases and contaminating groundwater through bioleaching, composting is safer. The heat and acidic environment generated during composting minimize the risk of disease spread, especially when proper precautions are followed. Composting methods are broadly classified into aerobic and anaerobic processes. Aerobic composting includes techniques like windrow composting, where organic matter is arranged in piles, watered, and regularly turned. Vermicomposting, another aerobic method, uses worms to break down waste, producing nutrient-rich fertilizer as a byproduct.

This study focuses on composting, examining the role of microbes and insects in the process, as well as the effects of compost on soil health, plant growth, human health, and crop yields. Additionally, it highlights the challenges of bringing compost products to market in Pakistan and the need to raise awareness among farmers about the long-term damage caused by chemical fertilizers, which ultimately degrade soil quality—a critical issue in Pakistan.

Keywords: Composting, Organic waste, Soil health, Sustainable waste management, Pakistan

INTRODUCTION

When choosing an eco-friendly method for waste disposal, composting stands out as an effective solution. It not only eliminates waste but also produces compost, a natural alternative to chemical fertilizers (1, 2). Chemical fertilizers are known to cause health problems, contaminate groundwater, spread diseases, and produce nutrient-deficient crops (3, 4). Composting offers a smarter solution by avoiding these harmful effects, enriching the soil with nutrients, and preventing the spread of disease (5, 6). Additionally, it is more cost-effective than purchasing chemical fertilizers (7, 8). However, despite these benefits, 70% of crop production today still relies on chemical fertilizers (9).

To reduce disease in plants, animals, and humans, organic farming—based on composting—is emerging as a more sustainable agricultural practice (10, 11). Compost is an excellent fertilizer for growing nutrient-rich crops (12). The soil, often referred to as the "skin of the Earth," is essential for life but is increasingly affected by various factors, leading to soil erosion (13, 14). Over the past 150 years, half of the Earth's topsoil has been lost (15). Millions of hectares of land in Pakistan, including Balochistan, have been degraded due to pollution and the excessive use of chemical fertilizers (16, 17). Land degradation poses a significant threat to the environment and food supply (18, 19). When the land is lost, it directly impacts the availability of fruits and vegetables (20, 21). This problem is particularly severe in hilly areas and regions with high rainfall, where soil erosion strips away the fertile top layer, organic matter, nutrients, and beneficial microbes (22, 23).

Organic matter helps protect against nutrient loss in soil (24). Collecting plant, vegetable, fruit, and animal waste can improve crop health and yield nutrient-rich harvests (25). Although composting is an age-old method, it is often underutilized (26). Composting can reduce the need for chemical fertilizers and create biofertilizers that are sustainable, protect against soil erosion, and increase crop yields (27). The process of breaking down plant and organic waste produces a dark, crumbly, soil-like substance called compost (28,



29). This nutrient-rich material improves soil health and is often referred to as "black gold" (30). The quality of compost depends on the type of organic waste used and factors such as oxygen, water, and heat (31). Although compost may have lower nitrogen content than traditional fertilizers, it provides essential organic matter to the soil, making it a valuable resource for sustainable agriculture (32).

COMPOSTING

Composting is a process in which organic waste is broken down into simpler chemical substances by microorganisms (33, 34). The product of this process, known as compost, is a natural byproduct rich in essential nutrients required for plant growth (35). In composting, organic waste is placed in a compost pile where, with adequate amounts of water, oxygen, and heat, it is converted into useful compost, releasing CO₂ as a byproduct (36). Anaerobic composting, on the other hand, produces methane gas (37).

To produce high-quality compost, it is essential to maintain a proper carbon-to-nitrogen (C) ratio, ideally 30 parts carbon to 1 part nitrogen (38). Compost is often referred to as "black gold" because of its value in recycling nutrients and making them available for plant use (39). Primarily, composting provides organic nutrients, which are crucial for healthy soil and plant growth (40).

In Pakistan, compost is sold in both urban and rural areas due to its environmental benefits, such as reducing pollution and producing nutrient-rich organic material (41). Large-scale composting involves the conversion of wastewater, agricultural waste, kitchen scraps, and organic waste from commercial areas into compost, which is then sold to nurseries and large farms (42). Although raw organic waste can be applied directly to farmland, this can lead to challenges such as insect proliferation during the composting process (43).

Proper decomposition requires maintaining the right temperature, which demands careful management (44). Unlike landfills, storing waste for composting contributes less to water pollution (45). Ultimately, it is up to farmers to decide whether to use compost as a natural fertilizer, as it is a microbial degradation process that enhances soil health and sustainability (46).

AEROBIC COMPOSTING

Aerobic composting involves the breakdown of crop residues, livestock waste, and other non-living organic materials into a dark, crumbly, earthy substance that enriches the soil with nutrients (47, 48). This process relies on various microfauna such as nematodes, mites, spiders, centipedes, earthworms, and ground beetles, as well as microorganisms like bacteria, fungi, and actinomycetes (49, 50). These organisms decompose organic matter in the presence of oxygen, producing a humus-like material known as compost (51).

The efficiency of aerobic composting is influenced by environmental factors such as oxygen levels, temperature, moisture, the nature of the substrate, and the microbial population (52). Like all living organisms, the microbes involved in composting require nutrients for growth and reproduction (53). They obtain carbon, nitrogen, phosphorus, and other macro and micronutrients from the organic residue. Oxygen and moisture are absorbed from the environment (54). During this process, a large amount of energy is released, raising the temperature to around 60-70°C, which is sufficient to kill pathogens (55). As the organic matter decomposes, carbon dioxide is released into the atmosphere (56). Once decomposition is complete, the temperature decreases, leaving behind a dark, crumbly substance rich in humus, along with living and dead microbial cells—this is the final compost product (57).

Aerobic Composting Equation:

Complex organic waste + moisture + O₂ → compost + CO₂ (58)

ANAEROBIC COMPOSTING

Anaerobic composting is carried out by microorganisms that do not require oxygen (59). Organic waste is deposited into pits and covered (60). During this process, methane gas is produced, which can be used for cooking and heating in winter (61). Thus, anaerobic composting yields two useful products: methane gas and compost, which enhances soil fertility while also reducing pollution (62).

Anaerobic Composting Equation:

Complex organic waste + soil → compost + methane gas (63)

TYPES OF ORGANIC WASTE FOR COMPOSTING

Organic waste suitable for composting includes a wide range of materials such as plant waste from gardens, manure from livestock (cows, pigs, camels, goats, sheep, and dogs), animal blood, urine, and human waste, as well as kitchen scraps (64).

Brown sources of carbon	Green sources of nitrogen
Saw dust, paper, wastes of dry fruits and garden waste etc. (65)	Kitchen scraps, Human and animal waste etc. (66)

This classification helps balance carbon and nitrogen sources, ensuring optimal composting conditions for efficient organic waste breakdown.

METHODS OF AEROBIC COMPOSTING

VESSEL COMPOSTING

This method involves composting organic material in a closed container or vessel, using forced aeration and mechanical turning to aid the process. While effective, it requires labor and is relatively expensive (67).

WINDROW COMPOSTING

In this method, organic waste is arranged in long piles and left for passive aeration. It is a slower process compared to vessel composting (68).

STATIC COMPOSTING

A traditional and cost-effective method of composting, static composting requires more time but is less expensive than other methods (69).

VERMICOMPOSTING

This method uses earthworms to consume organic waste, with their excretions forming compost rich in essential nutrients like nitrogen, phosphorus, potassium, and calcium, which are vital for soil fertility (70).

COMPOSTING PROCESS

Composting can be either aerobic or anaerobic. Aerobic composting requires oxygen, water, and porosity to stabilize organic waste. It is commonly controlled by factors such as temperature, oxygen levels, and moisture (71).

FACTORS AFFECTING COMPOSTING

ORGANIC MATTER CONTENT

Most plant and animal wastes undergo composting. Understanding the composition of organic materials used in the process is essential (72). Microbes in composting utilize carbon as an energy source and nitrogen for growth (73). The rate of degradation is influenced by the carbon-to-nitrogen (C) ratio. Materials high in nitrogen degrade faster than those with lower nitrogen content (74). An ideal C ratio for composting is around 30:1 (75). High C ratio materials, like rough plant matter, decompose slowly, while low C ratio materials, such as animal waste and young plant material, decompose rapidly (76).

ORGANISMS

Numerous organisms contribute to composting, classified into macro-organisms (e.g., mites, centipedes, snails, millipedes, spiders, beetles, ants, flies, nematodes, and earthworms) and micro-organisms (e.g., bacteria, fungi, and actinomycetes) (77). Macro-organisms physically break down material, while micro-organisms chemically decompose organic compounds (78). Aerobic bacteria, the most abundant decomposers, use carbon for energy and nitrogen for reproduction (79). Different bacterial species dominate at varying temperatures: psychrophilic bacteria operate at low temperatures (~20°C), mesophilic bacteria thrive at moderate temperatures (20–37°C), and thermophilic bacteria take over at higher temperatures (45–

70°C) (80). Compost turning helps regulate temperature, maintaining the optimal environment for decomposition (81).

AERATION

Adequate water and air are critical for microbial activity in composting (82). Microbes feed on organic compounds that dissolve in water, so moisture content is crucial (83). Optimal moisture levels range from 40–60% (18). If moisture drops below 40%, microbial activity slows, and organisms may become dormant (84). Conversely, excessive moisture (over 60%) can suffocate aerobic bacteria, leading to anaerobic conditions and unpleasant odors (85). Maintaining adequate moisture through watering, turning the pile, and protecting it from excessive rain during monsoons is essential (86).

TEMPERATURE

Composting begins with rapid decomposition, where the pile passes through stages of warming, high heat, cooling, and maturation (87). As complex organic compounds (e.g., carbohydrates and fats) are broken down, heat is generated, raising the temperature of the pile to 60–70°C (23). This heat is crucial for killing pathogens (88). Initially, the compost pile may contain harmful pathogens, but within 5–8 days, the temperature rises to a level that destroys them (89). Monitoring temperature with a thermometer is essential to ensure the process is progressing correctly (90).

pH

The initial pH of the compost pile is slightly acidic, around 6, due to the presence of plant sap (91). Microbes work best within a pH range of 5.5–8.0 (28). During the initial stages, organic acids form, supporting the breakdown of lignin and cellulose by fungi (29). As composting progresses, these acids are neutralized, and the mature compost stabilizes at a pH between 6 and 8 (92). If the pile becomes too alkaline, nitrogen loss through volatilization can occur, reducing microbial activity (93). Adding household ashes or eggshells can help balance pH levels (94).

PARTICLE SIZE

Smaller particles decompose more quickly than larger ones, so reducing particle size can accelerate the composting process (95).

APPLICATION OF COMPOST PILES

WAYS TO IMPROVE SOIL HEALTH

Increasing biomass production directly improves root biomass, contributing to soil enrichment as plant components return to the soil (96). Enhancing soil organic carbon through crop residue recycling, incorporating legumes in crop rotation or intercropping, and using green manure, farmyard manure, biofertilizers, and composting are key strategies to boost soil health (97). These approaches, combined with integrated nutrient management, are especially beneficial in rainfed areas (98). Composting agricultural waste, such as food scraps, leaves, and paper, is an important method where microorganisms and bacteria break down waste into nutrient-rich material, enhancing soil organic matter and increasing the population of beneficial microbes, which improve soil quality (99).

SUPPRESSION OF PATHOGENS

Compost helps create a disease-suppressive soil environment that promotes healthy plant growth while inhibiting pathogens (100). The mechanisms of disease suppression include induced plant resistance, direct parasitism of pathogens by beneficial microbes, nutrient competition, and the production of antibiotics by these microbes (101). Compost boosts plant vigor and resistance to pathogens while supporting the growth of beneficial microflora that may parasitize pathogens or produce antagonistic chemicals (102). Additionally, organic acids and ammonia in compost exhibit antagonistic effects on pathogens (103). Some compounds in compost may even trigger premature germination of pathogens, reducing their load in the soil (104).

COMPOST USE AND SOIL FERTILITY

Compost acts as a nutrient-rich soil conditioner that enhances soil quality by improving its physical and biological properties (105). It not only supplies essential nutrients but also makes them more available to plants (106). Compost has long-term benefits for soil nutrition, texture, structure, erosion control, and water retention (107). It reduces water runoff, prevents soil erosion, and minimizes the leaching of ammonium and nitrate into water systems, ultimately increasing overall soil fertility (108).

INCREASED CROP YIELD

Compost significantly enhances crop yield by improving plant productivity and enriching fruits, vegetables, and grains with essential nutrients (109).

ECONOMIC IMPACT

By producing biofertilizers domestically, the need to import expensive chemical fertilizers is reduced, allowing for investment in other sectors such as education and healthcare (110). Composting provides a cost-effective, sustainable alternative that improves soil fertility (111).

POLLUTION REDUCTION

Composting reduces soil, water, and air pollution caused by the excessive use of chemical fertilizers, which can leach into groundwater, degrade soil fertility, and contribute to air pollution (112). Organic waste, when improperly managed in landfills, releases carbon dioxide and harmful gases (113). Composting mitigates these effects by converting waste into a beneficial product that supports the environment (114).

DISADVANTAGES OF COMPOSTING

In the early stages of composting, especially when using animal manure, pathogens can spread, posing health risks (115). The decomposition process, particularly anaerobic composting, may produce unpleasant odors, such as ammonia (116). Large organic waste particles do not decompose readily, requiring them to be chopped or shredded before composting (117).

In countries like Pakistan, public awareness about composting is limited (118). Most waste is dumped in landfills, causing pollution through leaching, groundwater contamination, and greenhouse gas emissions (119). Pakistan has very few composting facilities, with only one plant in the Punjab province (120). Greater awareness and government intervention are needed to promote composting and reduce reliance on chemical fertilizers (121). If not properly managed, compost piles can become breeding grounds for insects like cockroaches (122). Proper handling and care, including using sterilized gloves and ensuring good hygiene, can prevent this issue (123).

SOLUTIONS

SAFE WASTE COLLECTION

Collect waste using sterilized gloves and shoes, and spray the waste with antiseptic before composting to reduce disease risk and insect growth (124).

INCREASING AWARENESS

Use television programs, seminars, and outreach efforts in schools, universities, and communities to educate people about the benefits of composting and its low cost (125).

GOVERNMENT SUPPORT

The government should provide financial support to small composting businesses, helping them establish composting plants across the country. This would reduce pollution and dependence on chemical fertilizers while creating jobs, particularly in underdeveloped areas like Balochistan (126).

CONCLUSION

Composting is an effective and sustainable method of waste management that enhances soil fertility, boosts crop yields, and reduces pollution. Unlike landfills, which contribute to leaching,



groundwater contamination, and air pollution, composting offers numerous environmental benefits. Anaerobic composting also produces methane, which can be used for cooking, heating, and generating electricity, addressing issues like gas shortages in Balochistan. Establishing composting plants across Pakistan would not only improve soil health but also create employment opportunities, particularly for young graduates. The goal is to spread awareness and promote composting as a viable solution to environmental and economic challenges. Additionally, further research is needed to understand the factors leading to insect growth during the composting process.

Conflict of Interest:

Authors have no conflict of interest.

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