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Review Article

Organic production of cabbage (*Brassica oleracea* L.) for agricultural sustainability and healthy nutrition: An overview

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Abstract
Cabbage (*Brassica oleracea* L.) is a versatile and nutritionally dense cruciferous vegetable with a long worldwide history of cultivation. This review explores the organic production methods of cabbage, emphasizing their pivotal role in fostering agricultural sustainability and promoting healthier nutritional practices. Organic farming principles, excluding synthetic pesticides and fertilizers in crop production, improve soil health, biodiversity conservation, and ecological balance. In cabbage cultivation, organic farming practices play a crucial role in promoting environmental health and human well-being. By avoiding synthetic chemicals, these methods help prevent water and soil pollution while fostering natural ecosystems. Organic techniques like crop rotation and composting enhance soil fertility naturally, improving overall soil health. This approach also benefits human health by reducing exposure to potentially harmful substances, resulting in safer food for consumers and a healthier work environment for farmers. Ultimately, organic practices offer a sustainable model for agriculture that balances productivity with environmental stewardship and health consciousness. Furthermore, organic cabbage production aligns with consumer preferences for chemical-free, nutritious foods, offering higher levels of essential nutrients, antioxidants, and phytochemicals than conventionally grown counterparts. The review delves into various organic management strategies for cultivating cabbage using organic fertilizers derived from recycled plant and animal wastes alone and in combination with microbes. Overall, this review underscores the significance of organic farming practices in advancing agricultural sustainability and ensuring access to nutrient-rich (carbohydrates, protein, vitamins, minerals, and dietary fibers) cabbage to promote human health and well-being.

Keywords: Cabbage, Suitability, Fertilizers, Organic farming, Manure, Sustainability

INTRODUCTION

Cabbage (*Brassica oleracea* L. var. *capitata* L.) is a widely cultivated biennial crop in the Cruciferae family, with a chromosome number of 2n = 18 (Zheng *et al*., 2023). It is utilized as a fresh or cooked vegetable and for the preparation of processed products (Chatterjee *et al.,* 2012; Kumar *et al*., 2022). Originating from Western Europe and the Western Mediterranean, it thrives on ledges of chalky cliffs. It is the fifth most important vegetable crop (Gelaye and Tadele, 2022), a vital vegetable crop grown on five continents namely Africa, Europe, Asia, America and Australia (Asamoah et al., 2021) and in over 90 countries, covering 3.1 million hectares globally (Ali and Kashem, 2018). Fig. 1 illustrates the production of cabbage in the ten leading producing countries. Its cultivation is essential for income and nutrition but heavily depletes nutrients, necessitating fertilizers. However, the extensive application of chemical fertilizers globally has led to soil degradation (Grubben and Denton, 2004; Hossain *et al*., 2024). In this context, organic cabbage production is crucial in providing quality food and maintaining soil health. While there is a limited number of rigorously conducted studies comparing organic and conventional farming, this article aims to review various aspects of organic cabbage production, including its nutritional quality, health benefits, challenges, and opportunities, as well as organic farming practices, and emerging trends in the organic agriculture industry.

Organic agriculture, often referred to as biological or ecological agriculture, is a growing field that emphasizes conservation-oriented farming practices, sustainable resource management, and environmental stewardship (Reganold and Wachter, 2016). This approach has gained attention in North America and Europe, focusing on crop rotation, natural pest management techniques, diversification of crops and livestock, and soil quality enhancement by adding compost and animal and green manures (USDA, 2000). Globally, 33% of the world's farmland is moderate to highly degraded, affecting the long-term health of ecosystems and local people's livelihoods, particularly in dryland areas (FAO, 2017). Organic agriculture significantly addresses two of the world's most pressing issues: climate change and food security (Ali and Kashem, 2018). Organic farming practices, such as the use of farm residues, mulching, cover crops, farmyard manure application, crop rotation, intercropping, green manure incorporation, green fallow practices, animal manure utilization, cultivation of nitrogen-fixing plants, water conservation methods, soil pH adjustment, soil testing procedures, composting, adoption of the push-pull management strategy, zero tillage practices, utilization of bio-slurry, liming, implementation of cover crops, certification processes, and processing methods, can help decrease the negative environmental impact of excessive chemical fertilizer use and promote sustainable agriculture (Aksoy, 2011; FiBl and IFOAM, 2021). Organic fertilizers, such as poultry and chicken manure (El-Sharkawy and Abdel-Razzak, 2010), are environmentally friendly and improve soil health, water-holding capacity, high cation exchange capacity, and low bulk density, fostering a diverse population of beneficial soil microorganisms (Citak and Sonmez, 2010; Muhammad *et al*., 2007; Ogedegbe and Law-Ogbomo, 2013; Laczi, 2015; Liu *et al*., 2024). However, the transition to organic farming can also present challenges, such as increased production risks due to pests and diseases (Chen, 2006). As depicted in Fig. 2, organic cabbage production is a promising approach to addressing environmental challenges and promoting sustainable agriculture. By implementing various organic farming techniques, farmers can improve soil health, reduce the use of chemical fertilizers, and contribute to a more sustainable and resilient food system.

Effect of organic sources on soil physical, chemical, and biological properties

The application of organic fertilizers has been shown to enhance soil quality by improving soil physical, chemical, and biological properties (Hsu and Lai, 2022). Organic manures enhance phosphorus availability, soil organic carbon, nitrogen use efficiency, efficient nutrient cycling, and reduce the pH of alkaline soils and bulk density (Mahmood *et al.,* 2017; Sharma *et al.,* 2019). The addition of organic fertilizers enhances soil porosity, soil moisture content, and water-holding capacity while reducing soil compaction and bulk density (Papini *et al.,* 2011;). Organic matter added through organic sources of nutrients benefits soil quality through their humified fractions, which is the most stable organic carbon reservoir in the soil that stabilizes soil structure (Piccolo *et al*.. 2005). Cow dung is a valuable organic fertilizer due to its nutrient content, particularly nitrogen, phosphorus, potassium, and sulfur, which are crucial in promoting the growth and yield of cabbage crops. Poultry dung exhibits a pronounced liming effect, making it particularly well-suited for acid soils (Shahariar *et al*., 2013). The process of soil amendment reduces soil acidity, thereby protecting crops against aluminium toxicity (Reza *et al*., 2016). Vermicomposting is a viable, cost-effective, and expeditious technique for effectively managing solid wastes using earthworms for decomposing and stabilising organic wastes (Payal *et al*., 2006). This approach offers the potential to access readily available nutrients, growth-enhancing substances, and a variety of beneficial microorganisms, such as nitrogen-fixing, phosphorous-solubilizing, and cellulose-decomposing organisms (Suthar, 2012).

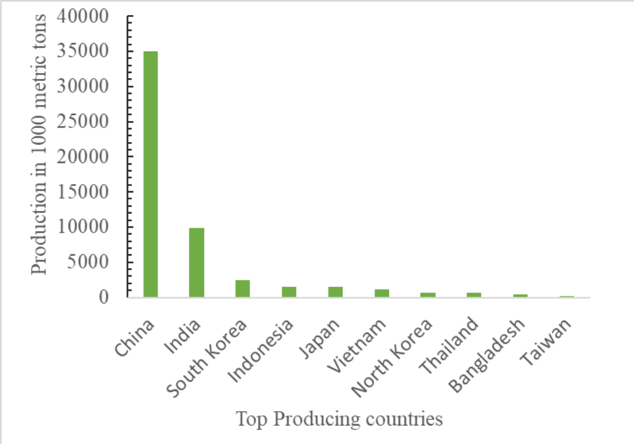

Fig. 1. *Asia-Pacific (APAC): Cabbage Production by Country 2022 | Statista, 2022.*

Furthermore, vermicomposting is characterized by a higher content of organic matter, nitrogen, phosphorous, sulfur, calcium, and magnesium (Zahid, 2001). However, the effect of organic fertilizers may not be immediate and could take time to be effective. For example, Ceronio *et al*. (2012) found that the impact of fertilizers was not significant in the first season but was seen in the second season. Straw incorporation is another way of improving soil properties whereas according to Di *et al.* (2021), straw is a considerably underestimated organic carbon source with potential soil eco-

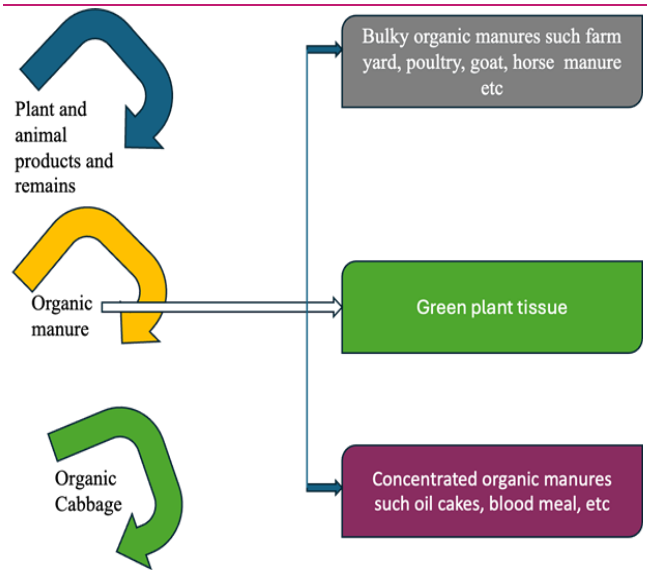

Fig. 2. *Organic sources reviewed in the present study*

logical functions, and its decomposition in soil influences the dynamic aggregation process of soil organic matter and other nutrients such as potassium. Straw incorporation is reported to contribute to soil nitrogen content and availability (Zhang *et al.,* 2016). A substantial improvement in soil health was observed in nutrient availability, physical stability, and microbial diversity due to the application of drum compost and traditional vermicompost (Goswami *et al.,* 2017). Manure Application increased organic phosphorus in the soil and gave a yield increase of 18.2%–25.9% of cabbage (Liao *et al*., 2008). The use of organic manures has been proven to remediate agricultural soils. For example, Mulenga *et al*. (2023) reported that chicken manure application to Pb-contaminated soils reduced Pb concentration in plants despite increased Pb mobilization in soil. Manure amendments can render heavy metals immobile and non-bioavailable by various physicochemical means (Bernal *et al.,* 2006; Silviana *et al.,* 2016; Hossain *et al.,* 2024).

Out of the 12 organic sources reviewed in Fig. 3 above, blood meal exhibits the highest nitrogen (N) content at 12.93%, followed by mustard oil seed at 4.59% and poultry manure at 3.16%. Regarding phosphorus (P) content, the leading sources are dewatered fecal sludge at 6.45%, vermicompost at 4.58%, and mustard oil seed at 3.28%. For potassium (K), poultry manure ranks highest at 2.23%, followed closely by goat manure at 2.08% and mustard oil seed at 2.05%. The values are similar to those reported by Yara Fertilizers (2024); Clemson University Extension (n.d.); The TNAU Agritech Portal (n.d.) https://agritech.tnau.ac.in/.

Nutrient composition analysis

The analysis of these organic sources reveals critical insights into their nutrient profiles, particularly the macronutrients essential for plant growth: nitrogen, phosphorus, and potassium (NPK). Blood meal, primarily derived from animal by-products, is recognized for its exceptionally high nitrogen content, making it an excellent choice for promoting vegetative growth (Yara Fertilizers, 2024). Mustard oil seed stands out for its nitrogen content and significant phosphorus and potassium levels, suggesting its multifaceted role in enhancing soil fertility and crop yield (Sharma *et al*., 2023). Dewatered fecal sludge and vermicompost emerge as valuable sources of phosphorus, indicating their potential in addressing phosphorus deficiencies in soils, which is crucial for root development and flowering in plants. The potassium content in poultry manure, goat manure, and mustard oil seed further underscores their importance in supporting overall plant health and fruit development (Maseko *et al.,* 2021).

Comprehensive NPK sources

Among the organic sources analyzed, those providing a balanced supply of NPK include mustard oil seed cake, dewatered fecal sludge, vermicompost, poultry manure, and sheep manure. These sources supply essential nutrients and contribute to improving soil structure and microbial activity, which are vital for sustainable agricultural practices (Hossain *et al., 2024). Integrating these organic fertilizers into agricultural systems can significantly enhance* soil fertility and crop productivity. For instance, while lower in nitrogen than blood meal, poultry manure offers a more balanced nutrient profile. It improves soil organic matter, which is essential for maintaining soil health over time (Maseko *et al.,* 2021). The findings indicate that while blood meal is the richest in nitrogen, other organic sources like mustard oil seed and poultry manure provide a more balanced nutrient profile, making them suitable for diverse agricultural applications (Sharma *et al*., 2023). The strategic use of these organic fertilizers can lead to improved crop yields and sustainable farming practices, emphasizing the importance of selecting appropriate organic amendments based on their nutrient content and the specific needs of the crops being cultivated.

Agronomic practices for organic cabbage production

Organic cabbage production employs management techniques that prioritize long-term soil fertility, sustainable agriculture, and minimal use of synthetic inputs (Kumar and Parmar, 2024). Key agronomic practices include thorough soil preparation through ploughing, ensuring proper aeration (FAO, 2017), and applying organic fertilizers based on soil tests to provide essential nutrients and stimulate plant growth (Mahmood *et al.,* 2017). Cultural practices such as timely weeding, top-dressing, and integrated pest management (IPM) are crucial for maintaining crop health while reducing

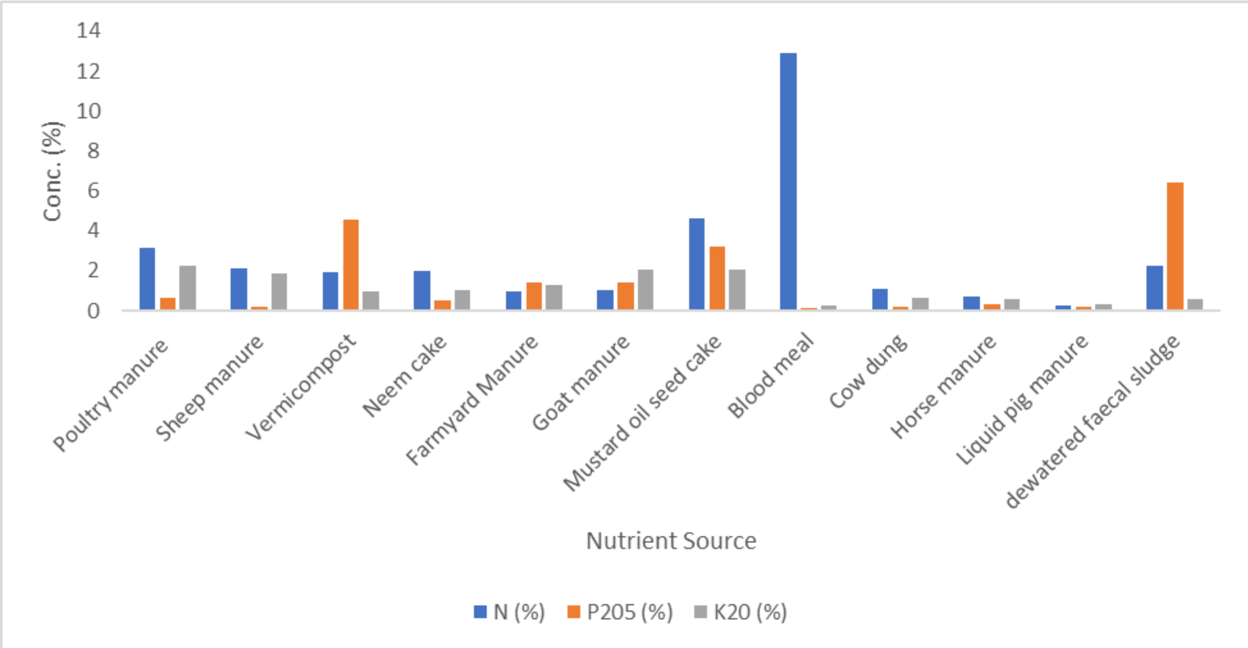

Fig. 3. *Chemical constituent of organic manures ; Adapted from: Poultry manure-Mbatha, 2008; Sheep manure-Tawfiq and Al-Sahaf, 2017; Vermicompost-Sajib et al., 2015; Neem cake-Mbatha, 2009; Farm yard manure-Zahradník and Petříková, 2007; Goat manure-Bhattarai et al., 2023; Mustard oil seed cake-Bhattarai et al., 2023; Blood meal-Citak and Sonmez, 2010; Cowdung-Debrah et al 2021; Horse manure-https://thisnzlife.co.nz; Liquid pig manure-Lim et al., 2007; Dewatered faecal sludge-Amoah, et al., 2016*

reliance on synthetic products (FAO, 2020). Harvesting should occur when outer leaves begin to yellow, indicating crop readiness, followed by proper post-harvest handling and storage to preserve quality (Chastain, 2024). Using organically produced seeds minimizes the risk of pest and disease introduction, while crop rotation strategies improve soil fertility and further reduce dependence on synthetic fertilizers. By adhering to these practices, organic cabbage production can achieve sustainability, environmental friendliness, high yields, and quality.

Nutritional quality of organic cabbage

Cabbage is a highly nutritious and valuable leafy vegetable (Islam *et al*., 2017) that is rich in minerals, vitamins, and dietary fibers (Dipankar and Subhra, 2016). It is also known to possess medicinal properties. The head of the cabbage is an excellent source of vitamins, minerals, and dietary fibers (Chatterjee *et al*., 2012; Debrah *et al*., 2021). According to Ijoyah and Sophie, 2009; Kumar *et al*. (2022), every 100 g of edible cabbage contains 92.1% moisture, 1.7% protein, 0.2 g fat, 5.3 g carbohydrates, 0.9 g fiber, 64 mg calcium, 26 mg phosphorous, 0.9 mg iron, 8 mg sodium, 209 mg potassium, 0.05 mg thiamine, 0.05 mg riboflavin, 0.3 mg niacin, 62 mg ascorbic acid, and 750 IU vitamin A. Cabbage is also rich in vitamin C, fiber, and vitamin K. Organic cabbage is known to contain more bioactive compounds such as glucosinolates, vitamin C, carotenoids, and polyphenols than conventionally grown cabbage.

Comparison of different organic manures on cabbage production

Organic fertilizers, such as cow dung, chicken manure, goat manure, horse manure, pig manure, vermicompost, neem cake, and urine, have been reported to exhibit superior nutrient uptake compared to artificial fertilizers. Several studies have compared the effectiveness of these organic fertilizers in organic cabbage farming. Reza *et al*. (2016) found that vermicompost shows promising potential as an organic alternative for enhancing cabbage output and nutrient absorption. Dipankar and Subhra (2016) compared the impact of farmyard manure (FYM), vermicompost, poultry manure, and a mixture of *neem cake* and *mahua* (*Madhuca longifolia*) cake on cabbage growth and yield with the neem and mahua cake mixture showing the highest yield. Chatterjee *et al*. (2012) reported that vermicompost emerged as a better organic nutrient source over farmyard manure when applied with inorganic fertilizers. Bhattarai *et al*. (2023) studied the efficacy of various organic fertilizers on cabbage, with poultry manure significantly increasing plant height, head diameter, and yield. Additionally, mustard oil seed cake and goat manure increased soil phosphorous and potassium content, respectively. Citak and Sonmez (2010) found that comparing of different organic sources is complex due to variations in nutrient contents, with different organic manures showing varying effects on cabbage growth and nutrient uptake. Furthermore, Lee *et al*. (2023) studied various types of liquid fertilizers and found that liquid bio-fertilizers exhibit superior performance in cabbage plant growth compared to other liquid fertilizers. Additionally, using pig dung as a fertilizer has been found to enhance plant nitrogen levels, but its application rate should be carefully managed to avoid hindering plant growth.

Vermicompost: A superior organic fertilizer for cabbage production

Based on the findings from multiple studies above (table 1), vermicompost emerges as the most effective organic fertilizer for cabbage cultivation. The results, carefully selected from numerous research papers, consistently demonstrate the superior performance of vermicompost in enhancing cabbage yield compared to other organic amendments.

Optimal application rate

The studies indicate that applying 10 tons of vermicompost per hectare yields the most promising results for cabbage production. This application rate outperformed 5 tons per hectare of nutrient-rich poultry manure and 20 tons per hectare of farmyard manure (Ali and Kashem, 2018; Yang *et al*., 2016). Similarly, Kumar *et al*. (2022) reported that vermicompost surpassed the performance of neem cake, farmyard manure (FYM), and poultry manure.

Comparison with other organic fertilizers

The findings of Adhikari *et al*. (2023) (table 1) show that 9 tons per hectare of vermicompost outperformed 4.8 tons per hectare of sheep manure. Furthermore, vermicompost provided better cabbage head weight than cow dung and NPK fertilized plots, as reported by Ali and Kasheem (2018). However, one study by Bhattarai *et al*. (2023) reported a different result, where goat manure performed better than vermicompost. This discrepancy may be attributed to factors such as soil type, climatic conditions, or the specific nutrient composition of the organic fertilizers used in the study.

Poultry manure's performance

Studies comparing poultry manure with small and big ruminant animal manures consistently reported better performance of poultry manure (Debrah *et al*., 2021; Bhattarai *et al*., 2023). This can be attributed to the higher nutrient content of poultry manure when similar application rates are used. In conclusion, the reviewed studies strongly suggest that vermicompost is the most effective organic fertilizer for cabbage production, with an optimal application rate of 10 tons per hectare. The superior performance of vermicompost can be attributed to its nutrient-rich composition and ability to improve soil properties, such as porosity, water retention capacity, and microbial activity. The use of vermicompost enhances cabbage yield and contributes to sustainable soil management and environmental protection.

Use of green manures to produce organic cabbage

In conventional crops, extreme doses of soluble fertilizers are used, but in organic cultivation, green manure associated with organic fertilization provides good productivity levels for the crop (Cordeiro *et al*., 2018). Green manure stands out in organic vegetable production as a complementary fertilizer alternative to organic compound incorporation, contributing to reduced production costs and improving soil physical, chemical, and biological features (Bento *et al*., 2020). The utilization of green manure legumes is advantageous not only for the cultivation of the subsequent crop but also for preserving of certain plant nutrients such as inorganic nitrogen and accessible phosphorus (Mappaona and Kitou, 1994). Researchers have compared green manures such as black velvet beans, jack beans, pigeon peas, and spontaneous vegetation (fallow) in two cropping systems (with and without incorporation of green manure plants) (Cordeiro *et al*., 2018). Jack beans and pigeon peas yield better fresh and dry weight. In contrast, better nitrogen content and accumulated nitrogen were obtained with jack beans, and it was concluded that the use of jack beans as a cover crop associated with the incorporation system is shown to be promising in producing cabbage (Cordeiro *et al*., 2018). The incorporation of green manure into soil offers several advantages. Increasing crop yields can enhance economic returns (Lim *et al*., 2012). Secondly, it reduces the reliance on chemical nitrogen (N) fertilizers. It mitigates the negative environmental consequences on water quality by utilizing excessive nitrogen in greenhouse soil and cultivating green manure crops during fallow periods (Lim *et al*., 2012).

Effect of biofertilizers on growth, yield and quality of cabbage

Biofertilizers are well documented in the literature, among which Azotobacter and Phosphate Solubilizing Bacteria (PSB) enrich the soil and crops by releasing nutrients and vitamins that promote growth. In the plant's root zone, Azotobacter fixes nitrogen from the atmosphere. It is an aerobic nitrogen-fixing bacteria that is free to live and can replace some inorganic fertilizers. Azotobacter inoculation reduces the need for nitrogenous fertilizers by 10–20%. When inoculated, Phosphorous Solubilizing Bacteria (PSB) solubilizes the previously inaccessible soil phosphorus by dissolving the fixed, insoluble phosphates in the soil. The PSB inoculation increases crop production by 10% to 30% (Kumar *et al*., 2022). Several previous studies have demonstrated that using organic manures alone is insufficient to attain the required growth, yield, and nutritional quality needed from cabbage. For example, Kumar *et al*. (2022) observed that with the application of Vermicompost + Azotobacter 10 + PSB, higher plant height, stem girth, and head girth were recorded com-

Table 1. Effect of different organic sources on the production of cabbage

Parameter	Showing finding from ton/ha of applications of different nutrient sources	Reference
Yield	$NC+MC_3$ > VC_{10} > PM_5 > FYM_{20}	Yang *et al.,* 2016
Head per ha	VC > NC > FYM > PM	Kumar *et al.,* 2022
Head weight	VC_9 > $BW_{0.23}$ > $PM_{4.8}$ >FYM_{29} > $SM_{4.8}$	Adhikari *et al.,* 2023
Yield	$IPNS_{1:2}$ > $Urea_{326\ kg/ha}$ > VC_{17} > $Biogen_{15}$	Islam *et al.,* 2017
Head weight	VC_{10} > $Cowdung_5$ > Inorganic	Ali and Kashem, 2018
Head weight	PM+NPK > PM_{40} > $_{250\ Kg/ha}$ NPK	Asamoah *et al.,* 2021
$Yield_{\ from140:50:80}$	MOC=PM=Obifert >GM >VC >FYM >NC	Bhattarai *et al.,* 2023
Head weight	$NPK_{250\ kg/ha}$ >PM_{10} >$Cowdung_{10}$ >GM_{10}	Debrah *et al.,* 2021

NC: neem cake, MC: mahum cake, VC: vermicompost, PM: poultry manure, FYM: farm yard manure, BW: black wonder, SM; sheep manure, IPNS: integrated plant nutrient system, MOC: mustard oil cake

pared to a single application of the organic manures. The treatment was also superior in producing maximum net weight of head, head yield per plot, head yield per ha, staying of heads, shelf life, total soluble solids, and days taken to head initiation. Upon comparison of chemical liquid fertiliser (CLF), fermented liquid manure (FLM) derived from pig droppings, and liquid biofertilizer (LBF) by Lee *et al*. (2023), LBF affected plant substances for sugar, ascorbic acid, and antioxidants in Chinese cabbage compared to CLF and FLM. The highest total polyphenol and flavonoid content, antioxidant activity, nitrite-scavenging capacity, and reducing power were observed in the LBF group. Biofertilizers can be combined with organic manures to enhance cabbage growth and yield. Green manuring with lupin 60 days before planting, sprinkling of horn manure to the soil at the time of land preparation, and application of well-decomposed farmyard manure at the time of land preparation are some of the recommended agronomic practices for organic cabbage production (Bento *et al*., 2020; Cordeiro *et al*., 2018).

Combined application organic manure and bio-fertilizers on cabbage

A remarkable effect on the physiological attributes after the incorporation of organic nutrients, especially in the form of vermicompost, farmyard manure, poultry manure, and biofertilizer, has been noticed in various vegetables. Mineralization, a microorganism-dominated process that transforms nutrients from their organic into their inorganic forms, which crops can then absorb, plays a significant role in this process (Hsu and Lai, 2022). Treatments comprising of poultry manure alone or in combination with *Azotobacter* proved to be more beneficial than Vermicompost or Farmyard manure alone or in combination with Azotobacter, as it improved yield attributes as well as yield of cabbage and gave maximum return as compared to other treatments. Among organic manure treatments, the combination of poultry manure and neem cake demonstrated superior performance compared to individual treatments (Srinivasan *et al*., 2014; Kumar and Parmar, 2024). Sarangthem *et al*. (2011) conducted an experiment to investigate the impact of two types of organic manure, namely vermicompost and FYM, and the presence of *Azospirillum* on cabbage. The application of vermicompost + *Azospirillum* resulted in the most significant cabbage yield and the highest concentration of nutrients (NPK) in the shoot and root of the crop. Additionally, this treatment led to increased post-harvest organic carbon and accessible NPK content in the soil. These findings demonstrate the significant superiority of vermicompost + *Azospirillum* overusing farmyard manure (FYM), similar to those reported by Rajput *et al.* (2022). In the study conducted by Upadhyay *et al*. (2011), it was observed that the combination of organic fertilizers with biofertilizer resulted in improved plant performance. Specifically, treatments that involved the application of recommended fertilizers along with seedling inoculation with biofertilizer exhibited higher dry matter in leaves (head), increased number of non-wrapper leaves, enhanced head yield, elevated levels of total carbohydrates, fiber content, carotenoids, and ascorbic acid (vitamin C) in the head. Verma *et al*. (2014) conducted a study investigating the impact of *Pseudomonas fluorescents* and humic acid on the growth, yield, and quality characteristics of Brassica oleracea L. The findings of the study indicate that the combination of a 100% recommended fertilizers package, along with seedling treatment using Pseudomonas fluorescens and humic acid, resulted in notable increases in plant height, dry matter in leaves (head), number of non-wrapper leaves, total carbohydrate content, maximum protein content in head, and head yield compared to the use of a single application (Haque *et al*., 2022). Ansari *et al*. (2020) found that the application of vermicompost significantly improved cabbage growth parameters, including plant height, number of leaves, and head diameter. The study also reported that vermicompost treatment yielded higher yields than other organic manures. Kumar and Parmar (2024) observed that the combination of vermicompost and Azotobacter produced the highest cabbage yield (117.17 Mt ha^{-1}) compared to other treatments. This study also noted that poultry manure alone had the lowest yield (86.78 Mt ha^{-1}) among the organic treatments tested. A study by Rajput *et al*. (2022) demonstrated that the application of 50% NPK ha-1 + Vermicompost + Azospirillum + Azotobacter + PSB resulted in the maximum cabbage yield (384.91 q/ha) and the highest concentration of nutrients in the soil after harvest. This treatment also led to improved growth parameters such as plant height, leaf width, and head diameter.

Combined application of chemical and organic manures on cabbage

The integration of chemical and organic fertilizers has demonstrated significant benefits in promoting sustainable crop production (Sur *et al*., 2010; Olaniyi and Ojetayo, 2011; Upadhyay *et al*., 2011; Vera-Núñez *et al*., 2016; Swami and Konyak, 2020). Therefore, it is imperative to stick to cultural practices, such as the proper application of fertilizers, to achieve optimal yields in cabbage cultivation. Combining organic and inorganic fertilizer can increase the yield and keep the environment sound (Hasan and Solaiman, 2012). Integrated nutrient management of fertilizers (organic or inorganic) has proven to be an efficient way to sustain yields, improve the soil's physical and chemical properties, and improve crop nutrient intake (Asamoah *et al*., 2021). Debrah *et al*. (2022) reported that chicken manure was at par with inorganic fertilizer but superior to other treatments. In contrast, cow dung and goat manure performed fairly well in the parameters measured. El-Sharkawy and Abdel-Razzak (2010) reported a high response of cabbage plants for fertilization with organic and mineral N fertilizers with humic acid, reflected as promoted plant growth and increased head yield and quality. Though the application of inorganic fertilizers may give better yield (Kiran *et al*., 2017; Kaur, 2020), it is important to consider the health of the soil and the end consumers. The application of a combination of 75% N urea + 25% N goat manure, 50% N urea + 50% N manure, and 75% N urea + 25% N goat manure with the addition of foliar fertilizer resulted in higher yields compared to single applications. The marketable yield obtained was 68.84 t ha-1, 66.5 t ha-1, and 64.75 t ha-1, respectively (Maghfoer, 2018). The most significant cabbage head length, diameter, and marketable yield were produced using organo-mineral fertilizers. Compared to applying NPK (15:15:15) fertilizer alone, organo-mineral fertilizers increased the maximum yield of various cabbage cultivars (Olaniyi and Ojetayo, 2011). Organic agricultural practices are associated with comparatively lower crop yields than conventional agriculture. While organic agriculture possesses potential to contribute to the development of sustainable farming systems, it is important to acknowledge that a singular strategy cannot adequately address the global challenge of feeding the planet in a safe manner. Instead, it is necessary to implement a combination of organic farming methods and other novel agricultural systems like combination with inorganic fertilizers (Reganold and Wachter, 2016).

The application of vermicompost + NPK and cow dung + NPK resulted in good and substantial effects on the growth and physio-morphological features, yield attributes, and overall yield, compared to single applications. A combination of 50% vermicompost and 50% cow dung exhibited superior performance. However, when evaluating the highest benefit cost ratio, a 50% cow dung blend and 50% NPK fertilizer proved more advantageous (Sajib *et al*., 2015). Applying a combination of organic and inorganic fertilizers substantially increased the soil's organic carbon content. The treatment that exhibited the greatest organic carbon content was the one that used organic manure along with NPK + Zn. The findings of the study indicate that integrated nutrient management plays a significant role in enhancing soil fertility by increasing the levels of major and micronutrients.It also helps preserve soil quality (Sur *et al*., 2010). Another study found that replacing 30% of chemical fertilizer with organic fertilizer increased cabbage marketable yield by 32.2% compared to compound fertilizer. The treatment also improved vitamin C, soluble sugar, and nitrogen use efficiency (Ren *et al*., 2021). A study by Kumar and Parmar (2024) showed that vermicompost combined with Azotobacter produced the highest cabbage yield (15.88 kg per plot), outperforming treatments using only organic or chemical fertilizers.

Combined effects of organic and inorganic as well as biofertilizers

The co-application of nitrogen (N) and straw-decomposing microbial inoculant is a cost-effective approach to improve soil fertility and crop productivity by accelerating straw degradation (Kalkhajeh *et al*., 2021). Nurhidayati *et al*. (2016) assessed the impact of types of vermicompost materials (spent mushroom waste, coconut husk and cow dung) and the population of *P. corethrurus* on the yield and quality of cabbage plants. The yield and quality of cabbage were significantly affected by the interaction between the type of vermicompost and the population of *P. corethrurus*. The application of the three types of vermicompost resulted in an average increase of 12% in sugar content and 57% in vitamin C content in cabbage. Moreover, the integration of chemicals and organic fertilizers has demonstrated significant benefits in promoting sustainable crop production (Sur *et al*., 2010; Olaniyi and Ojetayo, 2011; Upadhyay *et al*., 2011; Vera

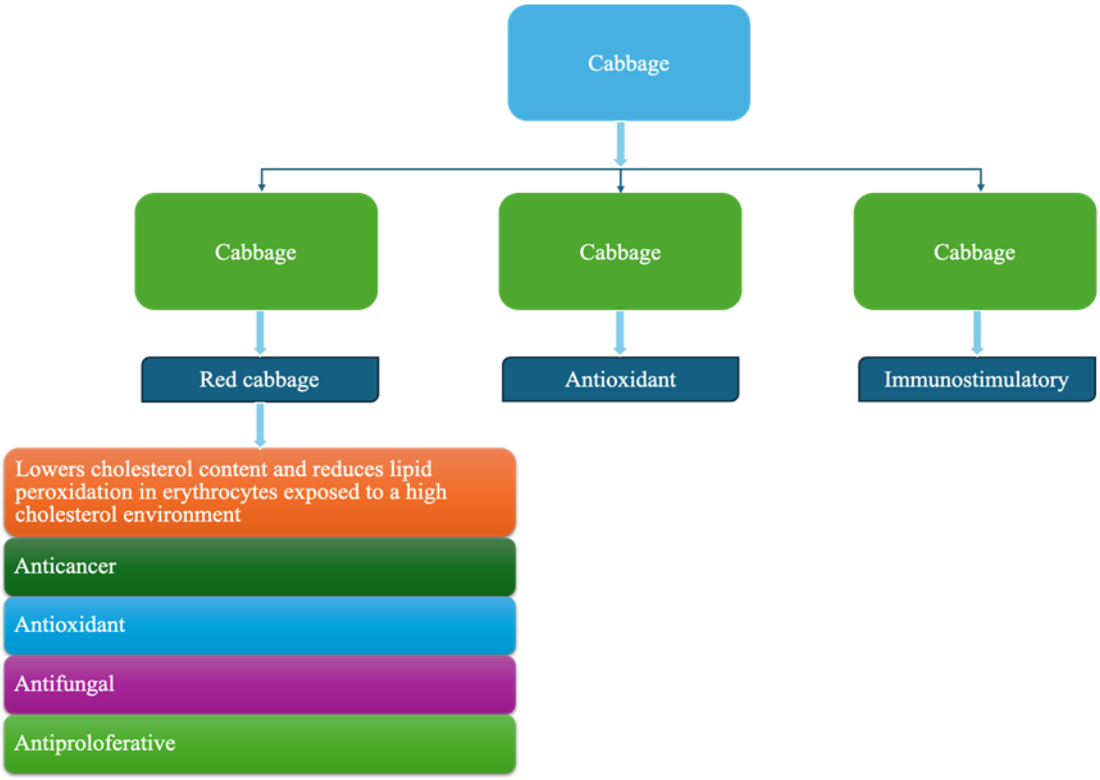

Fig. 4. *Health benefits of organic cabbage adopted from Ştefan and Ona (2020)*

-Núñez *et al*., 2016; Swami and Konyak, 2020). Therefore, it is imperative to stick to cultural practices, such as the proper application of fertilizers, to achieve optimal yields in cabbage cultivation. Combining organic and inorganic fertilizers can increase yield and maintain a healthy environment (Hasan and Solaiman, 2012). Integrated nutrient management of fertilizers (organic or inorganic) has proven to be an efficient way to sustain yields, improve soil physical and chemical properties, and improve crop nutrient intake (Asamoah *et al*., 2021). So, the co-application of N and straw-decomposing microbial inoculant and the integration of organic and inorganic fertilizers, can lead to improved soil fertility, crop productivity, and nutritional quality in cabbage cultivation.

Health benefits of consuming organic cabbage

Cabbage (Brassica oleracea var. capitate L.) is a nutritious and high-value leafy vegetable rich in minerals, vitamins, and dietary fibers (Ren *et al*., 2024). The health benefits of different kinds of cabbage is depicted in Fig. 4. Organic farming practices have gained popularity worldwide due to health problems arising from consuming unhealthy foods grown under intensive farming conditions, such as excessive pesticides or chemical fertilizers (Annex Publishers, 2018). Integrating chemical and organic fertilizers has demonstrated significant benefits in promoting sustainable crop production (Kumar & Parmar, 2024). Organic vegetable production research needs in the tropics and subtropics can provide food security and healthy diets for humans while being less harmful to the environment (EOS Data Analytics, 2024).

Organic cabbage production offers several advantages, including using organic fertilizers, which can improve soil fertility and crop productivity. The utilization of organic fertilizers, such as cow dung, chicken manure, goat manure, horse manure, pig manure, vermicompost, neem cake, farmyard manure, urine, and fecal sludge, has been reported to exhibit superior nutrient uptake in comparison to artificial fertilizers (Reza *et al.,* 2016; Dipankar and Subhra, 2016; Chatterjee *et al.,* 2012; Bhattarai *et al.,* 2023). However, several studies have demonstrated that using organic manures alone is insufficient to attain the required growth, yield, and nutritional quality needed from cabbage. For example, Kumar *et al*. (2022) observed that with the application of Vermicompost + *Azotobacter* 10 + PSB, higher plant height, stem girth, and head girth were recorded compared to single application of the organic manures. The treatment was also superior in producing maximum net weight of head, head yield per plot, head yield per ha, staying of heads, shelf life, total soluble solid, and days taken to head initiation. The co-application of N and straw-decomposing microbial inoculant is an efficient and inexpensive approach to improve soil fertility and crop productivity by accelerating of straw degradation (Kalkhajeh *et al.,* 2021). Organic cabbage production can contribute to food security and healthy diets for humans while being less environmentally harmful. Proper application of organic or inorganic fertilisers is essential to achieve optimal yields in cabbage cultivation. Integrated nutrient management of fertilizers (organic or inorganic) has proven to be an efficient way to sustain yields, improve the soil's physical and chemical properties, and improve crop nutrient intake (Asamoah *et al.,* 2021).

Challenges and opportunities in organic cabbage production

The world's population is rapidly increasing, which calls for more food production, where organic fertilizers are bulky and sometimes difficult to manage. The decomposition of organic manures takes time to be effective, especially for plant remains with high C/N ratios. Organic agricultural practices are associated with comparatively lower crop yields than conventional agriculture (Langemeier and Fang, 2021). While organic agriculture possesses the potential to contribute to the development of sustainable farming systems, it is essential to acknowledge that a singular strategy cannot adequately address the global challenge of feeding the planet in a safe manner. Instead, combining organic farming methods and other novel agricultural systems is necessary. There are notable obstacles that hinder the adoption of these systems (Knapp and van der Heijden, 2018). Nonetheless, a range of policy instruments will be necessary to support and promote their advancement and execution. Organic agriculture necessitates a larger land area to achieve equivalent food production compared to conventional agriculture, and its widespread implementation has the potential to pose a significant risk to global forests, wetlands, and grasslands (Muller *et al*., 2017).

Conclusion

Organic farming of cabbage aims to achieve several objectives, including the production of high-quality food, promoting a harmonious relationship with natural systems, optimizing biological cycles, preserving soil fertility, genetic diversity, and plant and wildlife habitats, maximizing renewable resources, establishing a balance between agricultural production and animal husbandry, and minimizing pollution. Animal farming generates over 1.4 billion tonnes of manure annually in the EU-27 (27 member states of the European Union) and the UK (United Kingdom) and considering soil biodiversity in manure management can enhance agricultural productivity, reduce farmers' costs, and enable positive environmental effects. Leguminous winter cover crops do not reduce soil nitrogen availability because they scavenge and fix nitrogen for succeeding high-nitrogen cabbage cultivation The successful cultivation of cabbage using organic fertilizers derived from recycled wastes has been studied. Future research should focus on finding guidelines for cabbage intercropping systems design to enhance quality and access premium prices.

Conflict of interest

The authors declare that they have no conflict of interest.

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