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Mastu Patel
Research Scholar, Department of Agronomy, School of Agriculture, Lovely Professional University, Phagwara, Punjab, India

Amit Raj
Research Scholar, Department of Agronomy, School of Agriculture, Lovely Professional University, Phagwara, Punjab, India

Maharabam Angelina Devi
Research Scholar, Department of Agronomy, School of Agriculture, Lovely Professional University, Phagwara, Punjab, India

Surya Dev Singh
PG Scholar, Department of Agronomy, School of Agriculture, Lovely Professional University, Phagwara, Punjab, India

Veerendra Kumar Patel
Research Scholar, Department of Agronomy, MGCGV Chitrakoot, Satna, Madhya Pradesh, India

Corresponding Author:
Mastu Patel
Research Scholar, Department of Agronomy, School of Agriculture, Lovely Professional University, Phagwara, Punjab, India

Crop residues management: A sustainable approach for rice and wheat production in Indo-Gangetic plains

Mastu Patel, Amit Raj, Maharabam Angelina Devi, Surya Dev Singh and Veerendra Kumar Patel

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Abstract
A major contributor to air pollution in the northern states of the Indian subcontinent and the entire Indian subcontinent is the burning of agricultural trash. The waste biomass is mostly burned in the North, from cereal crops like rice and wheat, and in other regions, from sugarcane leftovers. People impacted by this practice have shortened life expectancy, worsened health conditions, and are more likely to contract serious diseases due to the massive rise in numerous toxic gasses, such as sulfur compounds and particulate matter, released when agricultural leftovers are burned. This review provides an overview of the present tactics used to manage agricultural waste residues, with a focus on India. It also discusses the limitations of these strategies, as well as any proposed sustainable biotechnological solutions and their current status. This process can be greatly improved with the help of artificial intelligence systems for real-time monitoring and new mechanical stump removal techniques. Two major areas that are being promoted and have great promise are the creation of a commercial, decentralized market for the produced residues and the education of farmers and other interested parties, including policymakers, regarding their production and distribution. The best way to encourage farmers to act is to provide them with value items made from stubble. Among the many possible commercial uses for agricultural byproducts are: sustainable building practices, commercial product packaging, construction and roofing materials, biochar production for a variety of uses, mushroom cultivation substrate, and fermentation raw materials for the production of commercially valuable enzymes and other products. The success of the projects depends on government actions and assistance, in addition to commercial collaborations.

Keywords: Sustainability, residue management, biochar production, mulching

Introduction

The rice-wheat cropping system (RWCS) is the main cropping system in India's north-western Indo-Gangetic Plains (IGP). There are 34 million tons of rice crop residue produced from an area of 4.1 million hectares, primarily in the states of Punjab, Haryana, Uttarakhand, and western Uttar Pradesh (National Academy of Agricultural Sciences 2017) [1]. When rabi crops are sown, there is a very short window for disposing or using rice residues (Singh *et al.*, 2021) [2]. This window does not extend to crops like wheat, potato, or vegetables. Consequently, farmers burn all or part of the 80 percent of rice residue that is produced each year (Deptt. of Agriculture Cooperation & Farmers Welfare, 2019) [3]. India is one of the leading countries, burning of crop stubble or Parali after the harvest. India is largely blamed for 18% of the open burning in Asian countries, while Asia accounts for the vast bulk of biomass burning (34% globally) (Shaik *et al.*, 2019) [4]. Statistics from India's Ministry of New and Renewable Energy (MNRE) show that each year farmers produce an average of 50 crore tons of agricultural residue, with 9.2 crore tons going to the fire and 14 crore tons going to waste (Jain and Naik, 2022) [5]. Cereal crops account for 35.2 crore ton of crop residue, with 34% coming from rice and 22% from wheat harvests, according to the Indian Agricultural Research Institute (IARI) in New Delhi (Singh *et al*. 2018) [6]. The three states that produce the most crop residue are Uttar Pradesh (46 Mt), Maharashtra (60 Mt), and Punjab (51 Mt). The global demand for rice is the main reason why Asia has the highest residue burning rates compared to other continents when considering agriculture on a global scale.

This is likewise the case in India, where the rates of residue burning are 93% higher than in Pakistan and 30% higher than in China, respectively (FAOSTAT 2019). According to (Ravindra *et al*., 2019; Abdur-rahman *et al.*, 2020) [7, 8], 24% of the generated waste in the Indo-Gangetic region of India are burned in open field and massive air pollution, serious health risks for the local people are the long-term effects of this activity. A growing number of stakeholders are beginning to recognize the negative effects of open field burning, and farmers themselves are becoming more conscious of the need to find more effective ways to deal with the massive quantities of stubble that are produced. The Ministry of Agriculture in 2017, sought to promote the development of solutions for in situ crop management by creating the National Policy for Management of Crop Residue (NPMCR). Government policy-making agencies have released a number of rules that, when followed, significantly decrease harmful emissions and prevent burning (Alam and Sharma, 2022) [9]. In order to effectively address this crisis, it is crucial to regularly and promptly engage in dialogues regarding stubble burning, its causes, existing solutions, reasons why these solutions have failed, and what can be done to make a change.

Why do farmers start burning their stubble

In India, it is illegal to burn agricultural waste according to Section 144 of the Civil Procedure Code (CPC) (Datta *et al.* 2020) [10]. Indian farmers are fully aware of the regulations regarding the detection, prohibition, and penalties for burning crop leftovers. throughout spite of several efforts, both positive and negative, to discourage residue burning, it is still widely practiced throughout India and the neighboring countries where rice and wheat are grown. Reasons given for this practice include insufficient manpower to remove stubble, too little time between harvesting the current crop (rice) and sowing the next crop (wheat), and low industrial demand for the crop leftovers (Kadian and Meena, 2021) [11]. In addition, if no management strategy is put in place, the rice straw becomes a breeding ground for diseases like stem diseases, which in turn encourage the reproduction of pests like rats. As a result, the residue must be removed or managed promptly. As we've already established, burning stubble appears to be the easiest and fastest way for farmers to dispose of standing straw, and long-haul crops like wheat and rice exacerbate the issues we've already mentioned. After harvest, stubble burning is more common in India in the months of April–May and November–December. In spite of the lack of assurance, farmers continue to view stubble burning as an economical means of handling agro-waste. Consequently, establishing alternative procedures and providing farmers with profitable returns would greatly assist in encouraging them to abandon burning and adopt more sustainable methods of managing stubble waste, rather than simply imposing penalties and regulations on the activity.

Consequences of stubble burning

Burning is seen as an ineffective method of handling agricultural waste due to the harm it does to the atmosphere and other kinds of lifecycle (Singh and Nain, 2014) [12]. Open field with Stubble burning not only reduces sight and increases smog, but it also increases emissions of greenhouse gases and has many negative consequences on human health, such as respiratory ailments (Gadde *et al*., 2009) [13]. Results from the System of Air Quality and Weather Forecasting and Research (SAFAR) indicate that stubble burning is helping to lower the air quality in Delhi. One of the most polluted cities in the world is Delhi.

Particulate matter in the air increases by a factor of twenty in India's capital city every year due to the deliberate burning of crop waste (Worthington *et al*., 2017) [14]. The majority of air pollution comes from industrial sources (51%), followed by vehicles (27%), Diwali fireworks (5%), and burning stubble (17%) (Indian express 2019). Many beneficial soil microbes and farmer-friendly insects are killed off when fields are burned open. Loss of plant nutrients (N, P, K, and S), organic matter (CO2), and soil fertility are all negative effects of stubble burning on soil health (Kumar *et al*., 2019) [15]. Some of the most harmful byproducts of burning agricultural waste include: ammonia, sulfur dioxide, nitrogen dioxide, particle matter ($PM_{2.5}$) and PM_{10}, non-methane hydrocarbons, carbon monoxide, and non-methane volatile carbon (NMHC) (Khare *et al.,* 2021) [16]. According to TERI (2021), this practice is responsible for the annual release of 627 thousand tons of particle matter (PM_{10}) and 4,677 thousand tons of carbon monoxide into the atmosphere in India. A "toxic cloud" is produced, leading to a crisis in air pollution.

Given the abundance of proposed and implemented solutions to this problem, it is crucial to assess each one to determine which ones are most likely to be easily implemented and maintained. This article focuses on the different approaches that have been proposed and supported for the reasonable handling of stubble residue, mostly on the Indian subcontinent, throughout the years. In particular, this section covers active biotechnological interventions. The research also delves into the current state of stubble burning performs in nations outside of India and offers insights on how the Indian subcontinent might find a solution to this problem. Discover and implement additional economic applications for the biomass produced to transform this sector into a profitable and long-term focus for all parties involved. As the climate continues to change, it appears that all aspects of development and existence are at risk. This review is unique in that it presents real-life accounts of impoverished farmers who, after trying various stump management methods and theories, encounter setbacks and, ultimately, resort to burning biomass in their fields. Year after year, the problem remains, despite the abundance of alternatives to stubble burning. It is necessary to carefully examine current choices while also outlining new possibilities in light of these obstacles.

Stubble effects on people's health after the burning

A major contributor to fine particles (such as $PM_{2.5}$) in the Delhi and NCR region is the annual practice of burning crop stubble during winter. These microscopic particles ($PM_{2.5}$) penetrate the lungs and settle on the inside of the alveoli, posing a health risk to the general population and, in particular, the local farmers. The lung function is negatively affected by these particles, and the risk of cardiovascular disease and asthma is raised, as is the possibility of developing chronic bronchitis, impaired lung function, and mortality from lung cancer, regardless of the duration of exposure. The effects of stubble burning on human health were investigated in a case study carried out at Delhi's The Energy Resources Institute (TERI) by specialists from Punjab Agricultural University and the All-India Institute of Medical Sciences (AIIMS). Six villages in the Patiala district of Punjab's agricultural Nabha block were the subjects of the study, which focused on the issue of crop residue burning. It took place in two parts, in 2018 and 2019, before and after the stubble burning incident. Over 3600 people, ranging in age from 10 to 60, took part in the survey. During the two stages, the concentrations of $PM_{2.5}$, which are unburned carbon particles that are believed to be extremely harmful to respiratory health, more than doubled, increasing from 100 to 250 gm^{-3}. During the crop burning period, the majority of respiratory symptoms increased by a factor of two to three in all age categories (10-60 years). The majority of the respiratory symptoms were reported by the elderly (those aged 40 to 60 years) (Sehgal *et al*. 2021) [17].

Stubble Managing in India

Since stubble burning is most common in India, there needs to be extensive study, discussions, and actions taken. Concerns about crop waste burning have led to the launch of various projects in India aimed at improving agricultural stubble management. A number of government agencies and educational institutions are advocating finding new applications for the straw rather than throwing it out (Kumar *et al*.; 2015) [18]. As an alternative use for the biomass that is produced, farmers engage in activities such as using the leftover as mulch and composting it into agricultural fertilizer, both of which require minimum investment. To reduce soil erosion caused by wind and rain, conserve soil moisture, and manage weed growth, mulching is applied uniformly over the surface of the land. Mulching with rice straw increased water usage efficiency by 25%, increased wheat yield by 3%, and decreased water use for cropping by 3% to 11% compared to non-mulched crops (Gottipati *et al.* 2021) [19]. As a temporary measure, some Indian farmers let their fields lie fallow while they harvest paddy. Only then do they transplant the late rice crop. Instead of using food rice as a mulch, some Indian farmers keep the crop residue on the outside of the land by reusing mulch from the previous rice crop. The late rice transplantation pathway is mulched to ensure that the soil has enough moisture for the transplants, to suppress weed growth, and to reduce the breakdown of the rice (Sharma *et al*. 2011) [20]. Stubble has also found application in the production of compost, an organically rich agricultural material that is made by aerobically breaking down agricultural and other organic wastes. The procedure can be carried out in a controlled setting or in an open area. A good carbon to nitrogen ration is achieved by using raw materials with a high nitrogen content. It has also been discovered that rice and wheat stubble provide excellent composting source materials. However, there is a catch: rice takes a long time to decompose sometimes up to a year. The specialists have come up with a simple and fast way to turn huge piles of paddy straw into soil that is rich in biological nutrients. Preserving nitrogen and numerous other nutrients in the feed, this paddy residue compost takes around 45 days to be ready. Compost is an effective agricultural addition since it can raise crop yields by 4-5%. The labor-intensive and time-consuming process of composting has prevented paddy waste composting from gaining widespread recognition and usage in many regions, including Punjab and Haryana in India.

A). In Situ Incorporation of rice straw

Soil incorporation of CRs is good for nutrient recovering, but cultivating under is time-consuming and energy-intensive, keeps nutrients (like N) immobilized for a while, and fixes the high C:N ratio by adding more N fertilizer when the residue is mixed in (Shah *et al*., 2008) [21]. There is a temporary nitrogen shortage in crops that are grown soon after wastes are incorporated. This is because microbes immobilize soil and fertilizer N. The amount of time it takes for N to be immobilized and the amount of N that may be transferred from crop residues to the next crop are both affected by the decomposition period before the next crop is planted, the quality of the residue, and the environmental conditions of the soil. Longitudinal research by (Beri *et al.* 1995; Sidhu and Beri, 1989) [22, 23] found that compared to the residue removal treatment, yields of rice and wheat crops fell when CRs were added just before sowing the next crop. A successful in-situ management strategy for rice straw involves giving the wheat crop enough time (10–20 days) to germinate before adding the straw to prevent nitrogen deficit caused by nitrogen immobilization. The high expenses of inclusion as well as the energy and time demands mean that only a small number of farmers have chosen this method as an alternative to burning rice straw. In addition, according to research (Thuy *et al*., 2008) [24], planting wheat after adding rice residue delays the process by two to three weeks.

B). Use of Rice Straw as a Wheat Mulch

Utilizing rice straw as a mulch in no-till wheat is one innovative crop rotation management (CRM) strategy for the IGP that aims to decrease burning. Another strategy is to blend 1-2 t ha-1 of combine-harvested or even manually-harvested wheat straw and stubble with rice (Sidhu *et al*., 2009) [25]. CRs that stay on the soil's surface improve water and soil conservation, which in turn boosts crop yields. In many semiarid regions, maintaining farmland productivity is highly dependent on conserving water and soil resources. Evaporation from the soil surface can account for up to half of a crop's total evapotranspiration in these regions (Unger and Stewart, 1983) [26]. (Prihar *et al.* 2010) [27] found that the only way to decrease evapotranspiration by evaporation is to use mulching, which is the sole alternative to modifying the growth time of crops. One example of this is the rice growing in Punjab. All of the aforementioned advantages disappear when CRs are utilized as animal feed or extracted for other reasons. Consequently, maintaining soil productivity gets increasingly challenging. Nevertheless, by implementing suitable alternative practices, such as keeping certain residues, cultivating forages to replace CRs, using CA methods, and replenishing the nutrients found in grain and CRs, crop output can be sustained. Increased CR output as a result of better crop management might make it possible to restore some residues to fields while still removing enough to not harm the land. Wheat yield, profitability, and resource use efficiency have all been positively affected by the widespread adoption of zero-till practices in the northwest integrated grain production (IGP) (Erenstein and Laxmi, 2008; Ladha *et al.* 2009) [27, 29]. In no-till systems, it is not possible to manage CRs with tine-type openers. Uneven seed placement depths are produced by the continuous lifting of the instrument when dealing with heavy waste, which is exacerbated when straw piles up in the seed drill's furrow openers and the seed metering drive wheel loses traction. For no-till to work, it needs to be done consistently, and the soil needs to be covered with CR at least 30% of the time. A more extensive adoption of conservation agriculture will occur in the region as a result of using the Happy seeder, a new-generation planter (Sidhu *et al.* 2007) [30]. The Happy seeder can be used for direct drilling in standing or loose wastes, provided the residues are dispersed equally.

C). Managing of Wheat straw in rice

After harvesting wheat grains, several farmers in the northwest states of the IGP gather the straw using a specially developed equipment. They subsequently use it as fodder, leaving approximately 20 to 25% (1.5-2.0 t/ha) of straw in the field. Before the rice is transplanted, the field is prepared by burning the wheat straw that was left on it. Some farmers worry that leaving wheat stubbles in the fields may reduce the amount of rice that can be harvested. In contrast, a three-year field study conducted by the Department of Soil Science, PAU Ludhiana, found that adding partial wheat residue to rice yield had no negative effects. The study also confirmed that green manure can improve the sustainability of soil N fertility in lowland rice, as previously reported by (Yadvinder-Singh *et al.* 1991) [31].

The 60-65 days that remain following wheat harvest can be used for growing green manure crops such as mung bean (*Vigna radiata* L.), which can be used for both pulse grains and green manuring, or for growing pre-rice sole green manure crops (Yadvinder-Singh *et al*. 1991) [31]. (Aulakh *et al.*, 2001) [32] discovered that the rice yield was enhanced when wheat straw was combined with Sesbania aculeata, a green manure. In a long-term field study conducted on a loamy sand soil, researchers found that combining wheat straw with sesbania green manure, which has a low C:N ratio, and a full load of wheat straw reduced the negative impact of wheat straw alone on rice in the RW system. The study's findings were similar to those of (Sharma and Prasad, 2008) [33] which also indicated that applying wheat straw in combination with sesbania green manure or mung bean wastes improved the generally negative apparent N balances and increased cereal grain yield and agronomic N efficiency.

D). Managing stubble through biological approaches

Not only has mechanical removal of crop residues from the field been attempted, but there have also been interventions for in situ degradation of the residues. An investment of about twenty lakh rupees has been made by the Indian Agricultural Research Institute (IARI), Pusa, in a "decomposer capsule" that may be dissolved in a jaggery and gram four solution to create a liquid mixture. After 15 to 20 days of being sprayed with this mixture, the hard straw will be transformed into manure (Hindu 2020). Efficacious and rapid results have not been achieved with any other chemical composition. Instead of burning stubble leftovers, which is bad for the environment and wastes a lot of energy, biodegradation is a good option since it uses microbial and other biological treatments to make manure on the field (Sun and Cheng, 2002) [34]. Agricultural byproducts such as rice straw are prevalent on a global scale. For every kilogram of rice grain harvested, an estimated 1-1.5 kilograms of straw is produced. The worldwide production of byproducts is projected to be between 650 and 975 million tons per year (Swain *et al.* 2019) [35].

A high concentration of cellulose, lignin, and hemicellulose in rice straw makes it chemically distinct from straws from other crops and makes it resistant to degradation by many microbes. Therefore, bioaugmentation utilizing lignocellulolytic microbes can be a good approach. Research conducted by (Singh *et al.* 2011) [36] found that the use of microbes or their enzymes can accelerate the decomposition of stubborn compounds in stubble by speeding up their breakdown. A fungus called *Trichoderma viride* has shown promising results as a straw decomposer, and the National Rice Federation of Colombia has evaluated its application. Another study demonstrated that *Penicillium sp*. (HC1) could produce a combination of enzymes that could break down plant cellulose and hemicellulose. Compared to the previously used *Trichoderma reesei* mutants (ATCC26921), the results achieved by this multi-enzymatic complex are more effective (Pedraza Zapata *et al*. 2017) [37]. This efficiency is due to a combination of factors, including insufficient binding of these enzymes to the biomass's lignin component, strong - glucosidase activity, low sensitivity to product inhibition of the latter, and substantial specific cellobiohydrolase activity. There has been a lot of research into using fungus for biodegradation of wood and plant wastes, mostly focusing on white-rot species like *Phanerochaete chrysosporium*. An ongoing concern is the fungus species' sensitivity to cultivation conditions and its slow development on wood (Chang *et al*., 2012) [38]. National Centre for Organic and Natural Farming in 2015 (NCOF), an Indian foundation, established a culture of waste decomposers that been given the green light by ICAR (Verma *et al.*, 2024) [39]. Its intended function is as an agent that protects plants, one that improves soil health, so that organic trash can be composted quickly. The compound consists bacteria isolated from cow dung (NCOF) in the year 2018. Agri-biotech company situated in Pune, unveiled a novel product for farmers dubbed "Speed Compost," a microbial blend that recycles agricultural byproducts in the field instead of putting it in the fire. The substance is a blend of microorganisms, it consists of a mix of fungus, starch, cellulose, and bacteria that break down proteins. Fast breakdown is guaranteed by microbial consortiums and enzymes such as these and help farmers with the handling of agricultural leftovers both on-site and off-site promptly preparing their fields for the subsequent planting.

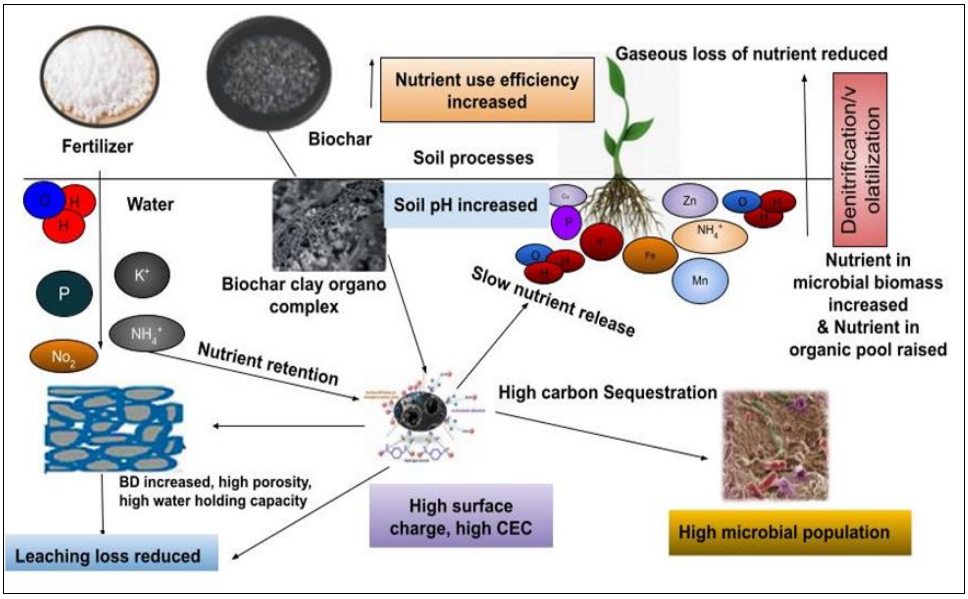

Fig 1: Providence of biochar application in the soil to repair various soil properties

E). Production of Biochar from crop residue: Biochar is a carbon-rich byproduct of the thermochemical metamorphosis known as slow pyrolysis, which takes place in an oxygen-poor environment (Weber and Quicker, 2018) [40]. According to (Brassard *et al.*, 2016) [41], it possesses a wide surface area ranging from 0.5 to 450 m^{-2} g^{-1}, a carbon content that is comparable to its parent material, and outstanding stability. Soil enhancement with biochar is possible, and it has been found to increase populations of beneficial soil microbes (Bhuvaneshwari *et al*., 2019) [42]. It improves the soil's water-holding capacity, surface area, bulk density, and pore distribution (Mukherjee *et al*., 2014) [43], as well as its ability to absorb inorganic and organic pollutants and decrease nutrient leaching (Novak *et al*., 2009) [44]. The soil is able to store nutrients in it. Biochar has several beneficial effects on different plant metabolisms and boosts the production of many crops. Biochar and compost were found to enhance the output of water spinach by 35.5% and *Basella* sp. by 22.1%, respectively (Vinh *et al.* 2014) [45]. According to (Sun *et al*., 2016) [46], biochar-based biofertilizers have a longer shelf life and can be used as an inoculum for various microbial strains. Farmers with smaller plots of land who aren't familiar with or able to afford contemporary farming techniques and inputs like fertilizers and pesticides can greatly benefit from biochar. Additionally, areas that have become infertile owing to soil erosion or low fertility can be helped by using biochar. Biochar can be used in a zero-budget natural farming method to boost production while decreasing the use of expensive chemicals. In this way, making biochar from stubble provides a long-term answer to the problems of stubble management and value product creation. In recent years, biochar has gained attention as a potentially useful product (Jyothsna *et al.*, 2019) [47]. The effectiveness of biochar produced from agricultural biomass in filtering out heavy metals, dangerous chemicals, and contaminants from wastewater and sewage has garnered significant interest as of late. Biochar has the makings of an effective and inexpensive adsorbent due to its remarkable physiochemical properties, such as its high carbon content, aromatic character, large surface area, and cation exchange capacity.

Valuable resources of stubble

A sustainable alternative to stubble burning that has recently gained traction is the utilization of crop wastes as a raw material for the production of other items. Additionally, this method gives farmers a convenient place to sell their excess harvest. This lignocellulosic raw material has been used in multiple documented cases recently. Efforts are being made to divert straw from incineration and into various other uses, such as making ethanol, biogas, mushrooms, regenerated cellulose, silica, and paper and paper board (Sharma *et al*., 2020) [48]. It is also possible for local companies to buy and collect fields stubble from farmers directly or via tiny decentralized representative bodies for their own usage. Farmers will benefit if they can find a way to dispose of their biomass as quickly as possible while still making money from a waste product.

The production of biogas or biomethane: In anaerobic digestion, organic carbon is broken down into methane and carbon dioxide (biogas) through a series of reactions that also produce trace amounts of nitrogen, hydrogen, hydrogen sulfide, and ammonia (Satpathy *et al.* 2016) [49]. Biogas can be produced at the lowest possible cost using organic waste from companies and farms as a raw source (Achinas *et al.* 2017) [50]. Biogas is among the best possibilities because it is cheap, efficient, and good for the environment. It can provide zero-waste solutions for biological waste management and is a renewable energy source that is nearly carbon neutral (Schoen *et al.* 2009) [51]. It has multiple potential uses, including as a cooking gas for homes, a fuel for automobiles, or even to feed into natural gas gridlines for cooking (McKendry *et al.*, 2002) [52]. Additionally, it is utilized in spark-ignition gas turbines and gas engines to produce power. Biogas production is a great intervention for shareholders and farmers on a tight budget because it is straightforward to implement and doesn't require high temperatures, unlike gasification.

Additionally, the biogas leachate, which is also known as digestate or wasted slurry, is a valuable by-product of the biogas process. Biogas can be produced at the lowest possible cost using organic waste from companies and farms as a raw source (Achinas *et al.* 2017) [53]. Biogas is among the best possibilities because it is cheap, efficient, and good for the environment.

The process of co-digesting agricultural leftovers with additional materials allows for the bulk creation of biogas (Lehtomaki *et al.*, 2006) [54]. This technology can be used by farmers to produce high-quality biogas that contains up to 70% more methane. Rates of India as the tenth-largest producer of biogas globally, and the country also has the highest number of biogas plants. The Indian Agricultural Research Institute (IARI) and the Indian Ministry of New and Renewable Energy (MNRE) are among the research institutions and laboratories that have come up with new ways to turn crop residues like stubble into biogas, which can be used instead of burning them. Producing biogas from agricultural byproducts isn't easy; not only does it involve labor-intensive harvesting from large fields, but also packaging, packing, storing, and transporting (Bhuvaneshwari *et al.*, 2019) [55].

Produces biofuels from agricultural waste: Another sustainable energy resource derived from biomass is biofuels, one of numerous forms of bioenergy. In the present scenario of increasing fossil fuel prices, this resource has enormous promise because it is ecologically friendly, emits zero net carbon dioxide, and releases a negligible amount of sulfur. According to (Gnansounou *et al*. 2015) [56], biodiesel and bioethanol are the two most popular forms of biofuels. According to (Singh *et al*. 2022; Patel and Gill, 2023) [57, 58], bioethanol was traditionally produced by fermenting sugar-based raw materials such as cornstarch, sweet sorghum and sugarcane. According to (Swain *et al*. 2019) [59], the idea of making bioethanol from leftovers that are high in starch was proposed. Reports indicate that various dry lignocellulosic biomass, including rice straw, wheat straw, and sugarcane bagasse, have the potential to produce 442 GL of bioethanol annually with a dosage of 1.5 Pg. When compared to other feedstocks such as wheat, corn, and sugarcane bagasse, paddy straw is typically the most preferred. Due to its extensive agricultural biomass resources, With the capacity to generate 291 GL of bioethanol from biomass, Asia is often regarded as the world's premier bioethanol producing region. Cites studies that suggest a potential production of 305.5-349.3 kg, or 387.08-442.6 L, of ethanol per ton of paddy straw. As per the research conducted by (Ahmed *et al.* 2017) [60], the highest recorded concentration of ethanol from raw paddy straw, measured in grams per kilogram, was 32 g kg^{-1}. This result was attained by employing a twin gear reactor (TGR), pretreatment with 4% (w/v) NaOH, and simultaneous saccharification and fermentation (SSF). Although the stated yield is lower than the theoretical maximum of ethanol generation from paddy straw, it might be raised by improving pretreatments, strains, and process parameters. This could lead to yields that are even closer to the theoretical yields. Pretreatment of crop residues with acids and enzymes improves the process and increases the bioethanol production. Wheat stubble can be pre-hydrolyzed at medium temperatures with diluted acid strength to dissolve its hemicellulose components and promote cellulose hydrolysis. Using this technique, several fermentable sugars were extracted from wheat stubble (Vancov and Mclntosh, 2012) [61]. Corn Stover, a combination of corn stems and corn leaves, is being investigated as a potential future energy source that is both affordable and environmentally friendly (Li *et al*. 2012) [62]. Researchers are focusing on using stubble as a source of fuel and energy, since this is the most promising and prominent alternative use of biomass.

Natural fibers

Another technique for converting waste into value is using crop residues to make eco-fibers. The fibers derived from agricultural products, known as bio-fibers, possess the ideal chemical and physical properties and composition for use in the pulp paper and textile sectors. Potential agriculture-based bio-fibers can be made from a variety of plant byproducts, including maize, wheat, paddy, barley, banana, pineapple, sugarcane, and coconut (Reddy and Yang, 2005) [63]. The pulp and papermaking industries have been using fibers derived from maize leftovers since 1929 (Li *et al.* 2012) [62]. Fibers from locally accessible biomass would be preferable than stock material, which would incur substantial transit costs. The lignocellulosic material found in agricultural wastes is abundant and can be used as a reliable supply of cellulose fibers. By utilizing chemicals, enzymes, and microorganisms (such as fungus and bacteria), the natural cellulose fibers can be extracted from lignocellulosic wastes through a process known as retting or degumming. To start the microbial action, the field is left wet for two to three weeks after harvesting is complete. The gum that binds the threads to the plant is pectin, which microbes help break down. Water retting is usually carried out by bacteria like Bacillus and Clostridium, while dew retting for fiber extraction is facilitated by *Rhizomucor pusillus* and *Fusarium lateritium* (Henriksson *et al.*, 1997) [64]. In their comprehensive research by (Devi *et al.*, 2017) [65] listed all the agricultural waste items that can be used to extract natural cellulose fibers for various industrial applications, including textiles, composites, and more. Ingredients such as rice, rape, wheat, maize, rye, hemp, sunflower, bean straw, vegetable and fruit leaves, soybean stalk and leaves, etc.

Nanomaterials based on cellulose: The agricultural byproducts, such as stubble, are being explored as a potential source for the production of nanocrystals and nanofibers due to their high cellulose and hemicellulose content. Nanofibers can be made from a wide variety of polymers, such as polysaccharides, cellulose, silk fibroin, collagen, gelatin, and keratin (Nasrollahzadeh *et al.*, 2019) [66]. The cell walls of all plants and some fungi include cellulose, a biopolymer that is abundant and stable (O'Sullivan *et al.*, 1997) [67]. One environmentally friendly natural resource that has potential applications in many bio-industries is cellulose, which is derived from plants. According to (Gundloori *et al.* 2019) [68], nanofibers can be synthesized utilizing a variety of methods, including electrospinning, self-assembly, template synthesis, and phase separation. There are two main types of nanocellulose, which are defined by the way they are extracted from biomass: cellulose nanofibers (CNFs) and cellulose nanocrystals (CNCs). According to (Siro and Plackett, 2010) [69], CNFs are usually made by mechanically manipulating plant fibers on a nanoscale. CNCs are composed of cellulose components that have undergone chemical hydrolysis using sulfuric or hydrochloric acid. The mechanical properties are diminished by the presence of amorphous portions in long fibers. The application of CNCs with supplementary processing steps removes this structural constraint (Hamad *et al.*, 2006) [70]. CNCs are ideal materials because cellulose has all the right properties: it's biocompatible, stable, biodegradable, nontoxic, and has primary hydroxyl groups readily available on its surface, so it's easy to modify its surface (Juntao *et al.*, 2016) [71]. (Xu *et al.* 2013) [72] found that nanocomposites consisting of CNCs and other polymers, such as PEO and PLA, had improved mechanical and dynamic properties, rendering them suitable reinforcing agents. Furthermore, CNC composites have various applications in bioimaging, batteries, drug delivery, tissue engineering, bio-scaffolds, bio-degradable films, biosensors, hydrogels for cell protection, and controlled delivery of medications at the site of injury. There has been a lot of discussion in the nanocomposites business about CNCs because of its remarkable qualities, which include mechanical strength, biodegradability, low density, unusual morphology, huge surface area, and nanoscale size. Using CNCs based on agricultural biomass, the polymer matrix and raw materials were made from a range of polymers. Nanocomposites are useful in many different fields. An integral part of food preservation is the use of polymeric packaging foil made from cellulose nanocrystals.

Produce of Enzyme: Important for both medical and industrial uses, enzymes produced by microbes outperform their plant and animal counterparts in terms of sustainability and activity. On top of that, microbes can produce enzymes on a massive scale with little investment of time or energy thanks to their fast multiplication capabilities, sensitivity to genetic modification, and metabolic variety. Due to their unique set of capabilities, microbes make for a great enzyme producer (Bharathiraja *et al.* 2017) [73]. Enzymes like cellulase, amylase, xylanase, protease, laccase, and many more can be produced by microbes by growing on lignocellulosic wastes. This approach significantly reduces production costs and makes efficient use of the bioprocess. Enzyme production from biomass derived from agricultural waste has been observed in a wide variety of bacteria and fungi. Researchers looked at several different types of agricultural waste in order to find an enzyme that could be synthesized using the *gibberella fujikuroi* bacterium. These included paddy stalk, bran, paddy stalk with bran, wheat bran, jowar spathe and stalk, and many more. According to (Mulimani and Patil, 2000) [74], the use of wheat bran as a substrate resulted in the maximum synthesis of α-amylase.

The present state and potential future directions of stubble burning: Many states in Northern India have dealt with the problem of stubble burning on a recurring basis in recent years. Following a 2016 judgement by the Delhi high court banning the burning of agricultural leftovers, the Punjab government fined farmers Rs. 73.2 lakh. The burning of agricultural fields is forbidden by Section 188 of the Indian Penal Code and the Air and Pollution Control Act (APC) of 1981. Still, millions of people's lives are negatively impacted by stubble burning, and the practice continues to harm the environment. From September through November of the year 2021, NASA satellites recorded the highest fire counts in the states of Haryana and Punjab from September 1, 2021, to November 29, 2021, there was a 7.3%

rise over the previous year, with 86,606 fire counts reported in the two states, according to NASA's VIIRS 375m satellite data (TOI 2021). Over the years, this technique has been linked to numerous catastrophes, including the degradation of soil and the significant loss of air quality. A farmer from the district of Ghazipur died after suffering serious burns sustained while frying wheat in a field.

The National Policy for Crop Residue Management (NPMCR) has not been enforced in Uttar Pradesh to put an end to stump burning (Yadav *et al.*, 2019) [75]. Farmers have expressed their frustration with the lack of other practical and long-term solutions, which has led them to embrace this technique.

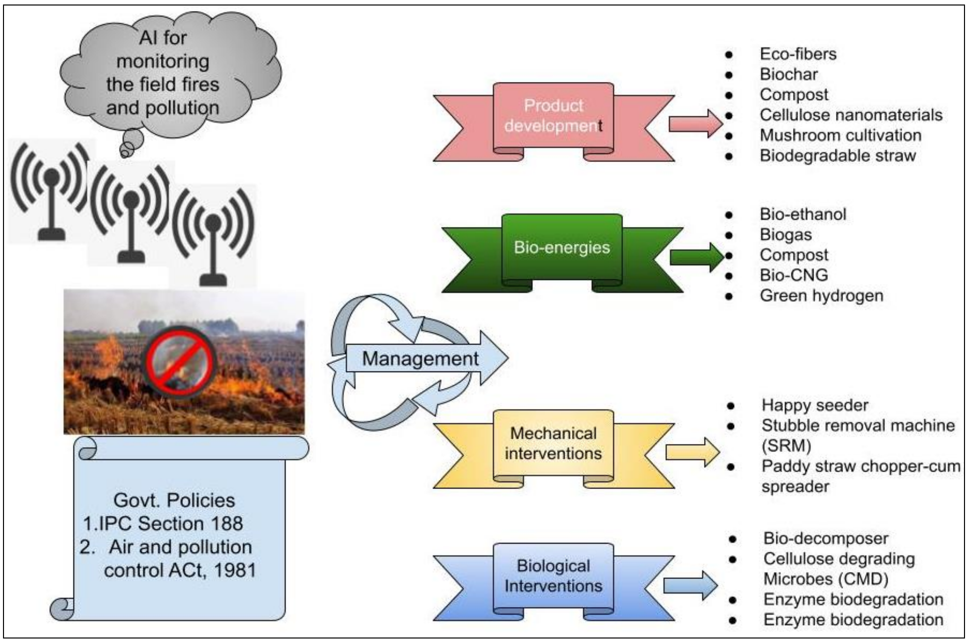

Fig 2: Sustainable strategies for managing stubble

Conclusion

A total prohibition on stubble burning will not work unless there are measures to deal with the amount of stubble waste produced each year and community awareness campaigns are supported. The degradation of soil health is just one of the many harmful effects of burning crop leftovers on human and animal health and the ecology. It is crucial to educate farmers about the drawbacks of stubble burning and the various environmentally favorable alternatives. This review aims to raise awareness about the negative impacts of stubble burning on the environment and ecosystem around the world. It also highlights more promising alternatives to stubble burning that are based on applications. The potential environmental benefits of reducing stubble burning and promoting sustainable crop residue management, as well as the significant economic value it may provide to the global agriculture sector, make it an attractive option for widespread adoption. The year-round availability of agricultural wastes makes them a promising raw resource for energy generation or valorization. To completely understand the effects of the legislation on agricultural crop residue burning and any potential constraints, further investigation is necessary. The current situation calls for stringent regulation compliance and severe punishments for rulebreakers, particularly in relation to polluters. Nevertheless, a decentralized supply of these waste products to value-adding factories needs to be set up until an extremely efficient on-site solution is implemented. While there is a lot of work going on to find a biological solution to agricultural residue, reducing air pollution from stubble burning will take time and a lot of cooperation and engagement between farmers and the general public.

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