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Minimum tillage a futuristic approach: Review

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Abstract
Modern agriculture now has a feasible and sustainable method known as minimum tillage. Due to its multiple advantages for the environment and agriculture, minimum tillage practices are becoming a growing trend among farmers worldwide. Reduced soil erosion, enhanced soil health, increased water infiltration, and higher crop yields can all result from the use of minimum tillage practices. The natural soil structure and the microorganisms that live there may be preserved with minimal soil disturbance during tillage, which is important for nutrient cycling and sustaining soil fertility. Furthermore, adopting minimum tillage practices can lead to a noteworthy reduction in greenhouse gas emissions, thereby modifying their contribution to climate change, since it necessitates fewer passes of machinery in the field. Minimum tillage practices also reduce labour costs and fuel consumption, thereby lowering production costs and increasing profits for farmers. However, minimum tillage practices require careful planning, as farmers need to choose the appropriate equipment and techniques to suit their specific soil and climatic conditions. Crop rotation, cover crops, and other soil conservation techniques must also be used by farmers to ensure the long-term viability of their land. Additionally, farmers who are used to using conventional tillage methods may need to change their thinking in order to adopt minimum tillage practices. Minimum tillage practices can provide significant benefits for the environment, agriculture, and the economy. Their adoption can help promote sustainable agriculture and contribute to global efforts to mitigate climate change. Education and outreach programs can help farmers understand the benefits of minimum tillage practices and provide support to ensure their long-term success.

Keywords: Conservation tillage, farming, minimum tillage, tillage

Introduction
Global discussions have revolved around the changing climate and its detrimental impact on agricultural production. In the context of global climate change leading to reduced precipitation, maintaining soil sustainability will be crucial for sustaining crop yields. This adverse effect has led to issues like soil erosion and a decline in soil fertility. Notably, soils worldwide contain 3.5% of the Earth's carbon reserves, in contrast to 1.7% in the atmosphere and 1.0% in living organisms, as pointed out by Lal *et al.* in 1994 [15]. The quality of soil structure holds significant importance as it greatly influences soil erosion, which is a naturally occurring process that cannot be entirely halted. Erosion is an ongoing, observable phenomenon that can manifest over various timeframes, from lasting centuries to being noticeable within a few years. To safeguard existing soil, it is imperative to plant trees and herbaceous plants within the soil. Trees and other vegetation help mitigate the effects of erosion caused by wind and rainfall, offering an effective countermeasure, as highlighted by Meryem and Funda in 2015.

A fundamental technique employed in agricultural practices is tillage. This process involves the mechanical alteration of soil arrangements, demanding significant energy inputs and expenses. Its objectives include preparing the soil for seeding, integrating fertilizers, manure, and organic matter into the soil, alleviating compaction, and managing weed growth. (Phillips *et al.*, 1980; Leij *et al.*, 2002) [23, 17]. The primary aim of soil tillage encompasses a range of immediate outcomes, including initial soil preparation for planting, creating an environment for seed germination, and ongoing field upkeep. However, excessive tillage, especially when carried out without retaining crop residues, can have detrimental long-term consequences on soil productivity. This is primarily due to issues like erosion and the depletion of organic carbon in the soil (Ahmed *et al.*, 1996) [1].

Conservation tillage refers to a category of tillage practices in which a minimum of 30% of the crop residue remains on the surface of the soil after planting.

This category encompasses various methods, such as no-tillage, shallow surface tillage, subsoiling, minimum or reduced tillage and the application of residue mulch (Jin *et al*., 2007) [11].

Conservation tillage is acknowledged for its superior effectiveness compared to conventional tillage when it comes to enhancing soil quality and boosting crop yields (Lal, 1989; Havlin *et al*., 1990) [14, 6]. Conservation tillage is recognized for its higher efficiency in improving soil quality and increasing crop yields when contrasted with conventional tillage (Holland, 2004; Iqbal *et al.,* 2005; Wang, *et al.,* 2008) [7, 10, 33].

The least amount of soil disturbance, such as ripping or planting at spot or in basins, constitutes minimum tillage. According to the fundamentals of minimum tillage, soil turnover should be limited by limiting soil disturbance to a specific region. In essence, it improves the soil structure, influences plant growth and development, thus increasing productivity. Minimum tillage encompasses any approach that reduces the conventional processes involved in cultivating plants. This pertains to tillage methods where minimal to no disruption of the soil occurs for the purpose of crop cultivation. It involves creating holes or furrows for planting seeds while leaving the rest of the field largely undisturbed, with visible crop residues on the ground. This approach has the advantages of reducing soil erosion, promoting the accumulation of organic matter in the soil, leading to improved chemical and physical soil fertility. Furthermore, minimum tillage signifies reduced labor, energy and time investment in ground preparation. As a result, cropping may be accomplished in a short period of time. Herbicides are typically used in minimum tillage farming practices to control weeds.

One or more of the following elements set it apart from conventional tillage

- Reduces operations
- Reduces disturbance to the soil
- Less energy is used
- A seedbed is prepared precisely at the spot where the seeds are to be sown.
- Crop residues remain on the surface and are not buried.
- Reducing the utilization of different equipment types

The goal is to carry out only essential tasks to create the ideal soil conditions for seed germination and the successful growth of crops. Additionally, it aims to reduce both human and machinery activity to prevent soil compaction and the disruption of soil structure, which, in turn, helps prevent soil erosion and conserves moisture. This approach also results in reduced labour and mechanical energy usage (IIRR and ACT, 2005) [9].

Minimum tillage practices include

Dibble stick planting

On an untilled field with crop residue and stubble, planting holes can be made with a planting stick or machete. To prepare planting holes, a trimmed hardwood branch from a tree is pointed at one end. The holes are arranged in rows with consistent spacing, facilitating weed management and the application of fertilizers or manure.

Stubble harrowing

This particular tool is employed to fragment agricultural debris, eliminate weeds, and loosen the soil. Subsequently, planting is conducted without further soil disruption, and crop remnants are retained on the topsoil.

Strip and spot tillage

Spot tillage is a soil management method that entails precise tilling only in the exact spots where planting is required. This approach minimizes soil disruption, preserves soil moisture, and effectively manages the soil. It's especially advantageous for establishing plantings on steep terrain, allowing work to be conducted on flat ground or on slopes, whether uphill or downhill. This technique reduces erosion by leaving crop debris as mulch and limiting soil disturbance. Moreover, since spot tillage isn't weather-dependent, field operations can be carried out nearly year-round. Consequently, this results in lowered per-acre fixed costs due to enhanced plant utilization (Texas A&M forest service). To achieve this, shallow planting depressions are gently created within untouched soil, where seeds are placed and subsequently covered. This technique is widely practiced across the Sahel region, encompassing countries such as Mali, Niger, Chad, and others. The sole equipment required includes a handheld hoe and a planting stick, enabling implementation in both arid conditions or immediately after rainfall (IIRR and ACT, 2005) [9].

The following steps involved are as

- Create small, superficial indentations in the ground, ensuring they are appropriately spaced apart. These holes should only be dug to the necessary depth for seed placement.
- Place the designated number of seeds into each hole and then cover them with soil.
- About two weeks after the crop initially sprouts, use a stick to make a hole approximately 10 cm away from each plant, and add fertilizer to the hole.

Advantages

- The need for labour is lower in comparison to traditional cultivation practices.
- Because of the labour factor and the need for a smaller land area, it is more acceptable to vulnerable households.
- The planting process is completed timely.
- There is no requirement for costly equipment. only a hoe and a stick

Disadvantages

- Difficulty may occur for controlling weeds.
- Prevent the formation of a compacted layer caused by consistently hoeing at a uniform depth.
- Crop root growth may not reach its full potential in this method compared to planting in basins, and the soil might not retain as much moisture.

Ripping

A ripper is an implement featuring a chisel-like shape that can be pulled by either an animal or a tractor. When used on the soil, it creates a shallow groove or slot typically ranging from 5 to 10 cm in depth, and it helps break up surface crusts. Ripping involves the action of making shallow, parallel furrows with a ripper without disrupting the soil between the planting rows. Typically, planting is carried out simultaneously, and the spacing between the furrows is determined by the crop's required distance. This approach has the potential to minimize or entirely eliminate the necessity for ploughing. (IIRR and ACT, 2005) [9].

Advantages

- As ripper attachments attach to a standard plough beam, they are less expensive than whole implements.
- Utilized for creating planting slots in dry soil, enabling early planting.
- Reduces soil disruption in contrast to plowing, resulting in reduced soil erosion and improved water infiltration into the soil.

Disadvantages

- Challenges arise when there is a substantial amount of surface residues as they can wrap around the ripper shaft.
- The soil surface is disturbed up to 30%.
- Presenting a moderate level of difficulty when employed on fields containing tree stumps.

Objective

The primary goal of this review paper is to assess the techniques associated with minimum tillage and their advantages concerning soil preservation, time efficiency, labour, crop yield and more.

Why use minimum tillage?

Modern farming practices have increasingly pronounced and identifiable social, ecological, economic and environmental consequences, largely due to escalating concerns about agricultural sustainability and the environment. Among seedbed preparation tasks, ploughing stands out as the most time-consuming operation. Minimum tillage approaches that don't necessitate ploughing are considerably rapider since they only disturb or fully till a small fraction of the 2 million pounds of soil (Shubeck and Kingsley, 1965) [27].

Minimum tillage presents a viable approach for cutting down on planting expenses. The operational costs, however, vary from farm to farm and location to location, contingent on the specific minimum tillage method employed. These costs are influenced by factors such as how frequently a farmer typically works the field using conventional methods and the total acreage under cultivation. To illustrate, a large-scale farm operator typically incurs lower per-acre expenses for each tillage operation since their depreciation expenses are distributed across a larger land area (Musgrave *et al.*, 1955) [20]. Each minimum tillage technique reduces the need for at least one pass across the field, and in some cases, multiple passes are eliminated. This time-saving aspect can be highly significant for farmers. Moreover, besides the time saved during land preparation and planting, certain minimum tillage methods can further enhance efficiency by allowing for increased cultivation speed.

Studies conducted in Indiana, Ohio, and Wisconsin have shown that minimum tillage practices can enhance water penetration, particularly in areas with sloping landscapes featuring dense, slowly permeable soils. On steeper slopes, the uneven seedbed typically associated with minimum tillage techniques is anticipated to diminish runoff, especially when the tillage process aligns with contour lines (Shubeck and Kingsley, 1965) [27].

Effect of minimum tillage practice on yield

Rusu *et al.* (2009) [25] evaluated minimum tillage soil systems employing para-plough, chisel, or rotary grape methods revealed versatile alternatives for fundamental soil preparation, germination bed readiness, and planting. These approaches proved optimal for fields and crops with moderate soil looseness requirements and served as effective technologies for activating natural soil fertility, reducing erosion, enhancing water retention, and facilitating timely planting. Through consistent application of the minimum tillage system over a four-year crop rotation cycle (including corn, soybean, wheat, and potato), notable improvements were observed in the physical, hydro-physical, and biological attributes of the soil. This led to a rebuilt soil structure, increased soil permeability, and improved overall soil drainage, facilitating rapid water infiltration. Consequently, the result was more productive soil, offering better protection against wind and water erosion while requiring less fuel for germination bed preparation. Yields obtained through the implementation of minimum tillage systems varied across crops. In comparison to conventional tillage, minimum tillage variants yielded between 92.1% to 97.9% in corn, 96.4% to 101.6% in soybean, 95.1% to 98.2% in wheat, and 82.4% to 93.4% in potato.

Leghari *et al.* (2015) [16] investigated the impact of three tillage methods - Conventional tillage, Reduced/minimum tillage, and No tillage - on the growth, development, yield, and yield components of bread wheat (Triticum aestivum). The results indicated that in both years, the Conventional tillage method led to significant improvements in nearly all aspects of bread wheat growth, yield, and yield-related characteristics when compared to reduced/minimum tillage and no tillage methods. Notably, it enhanced traits such as seedling emergence percentage, plant height, root system development, the number of main-stem leaves per plant, productive tillers per plant, spike-lets per spike, spike length, grain count per spike, and grain and straw yields per hectare. However, it's worth noting that over the two years, the reduced/minimum tillage approach yielded a higher marginal return compared to the other methods.

Ngugi (1987) [21] studied for the production of maize, two minimal tillage methods (strip and spot) were examined, each with three weed management approaches, and compared with a traditional tillage method. In a season characterized by relatively low precipitation, there were no significant variations in grain yield among the tillage techniques. However, minimum tillage did yield slightly better results than conventional tillage. The seed germination rate was marginally lower under minimum tillage compared to conventional tillage. Nevertheless, there was more rodent damage to the seeds under the conventional tillage method, ultimately resulting in no discernible disparities in plant populations between the various tillage methods.

Tolessa *et al.* (2017) [32] investigated how different tillage methods and nitrogen fertilization levels affect maize yield and its components. Three tillage systems, including minimum tillage with residue retention (MTRR), minimum tillage with residue removal (MTRV), and conventional tillage (CT) were tested in combination with three nitrogen levels: recommended, 25% less, and 25% more than the recommended rate. The experiments resulted in maize grain yields ranging from 4,649 to 8,030 kg/ha, with an average yield of 6,104 kg/ha. The study found a strong and positive relationship between grain yield and various yield components, especially total biomass yield and the weight of a thousand seeds. Regardless of the tillage method used, nitrogen treatment significantly increased grain production,

with an optimal fertilization rate of 92 kg/ha for minimum tillage maize.
Shubeck and Kingsley (1965) [27] assessed minimum tillage methods employed for growing corn, namely wheel track planting, hard ground listing, plough planting, and strip processing. These systems had various combinations and modifications, each with its own advantages, challenges, and limitations. The benefits of using these methods were significant and clear, as they reduced operating costs, saved time, conserved moisture, and reduced soil compaction. On the downside, challenges typically revolved around adapting machinery, managing weeds, placing fertilizers, achieving good crop stands, and maintaining yields. In most cases, these drawbacks could be minimized or overcome. It was observed that minimum tillage methods incorporating plowing were generally easier to refine and tended to be more successful in sustaining crop yields. While minimum tillage could be applied across a wide range of soil types, certain methods were better suited for challenging soil conditions.

Effect of minimum tillage practice on soil properties

Dayou *et al.* (2017) [4] studied the impact on soil fertility of both minimal and conventional tillage. Evaluation of this approach has been prompted by the long-term effects of conventional tillage, including soil compaction, soil erosion, and loss of soil fertility. Simplified cultivation methods (SCT) were used more frequently to solve these problems. It was observed that conventional tillage affects the soil's fertility and production after 5 to 6 years. SCT methods leave more agricultural byproducts behind and enhance the soil's organic matter index by reducing mineralization. Similar to zero tillage, the STC increases soil fertility and might reduce greenhouse gas emissions. Enhancing soil fertility results in increased output while reducing labour requirements. SCT creates a better environment for soil fertility recovery than traditional tillage. The particular direct seeder has to be produced to go together with the mechanization of these methods.
Bekele in (2020) [2] determined that soil tillage systems could be able to influence soil compaction, water dynamics and crop yield. These processes can be described as changes in soil respiration, soil microbial activity, and agricultural sustainability. Reviewing the impact of tillage practises on soil moisture conservation was the main goal of this article. Tillage impacts the physical characteristics of the soil (bulk density and infiltration rate), as well as the ability of the soil to hold water when compared to a control plot. The best method for maintaining soil health and obtaining the highest production was determined to be minimal tillage with 20% residue retention. The uses of MT and NT limit soil movement. When seeds were sown and throughout the early phases of growth, soil moisture levels were greater in NT and MT. In areas where there is a lot of wind and water erosion, conservation tillage is frequently practiced. The ability of the soil to catch and store water from precipitation or irrigation depends on the hydraulic qualities of the soil, such as water infiltration, hydraulic conductivity, and water retention, which are either directly or indirectly influenced by tillage practices. Tillage also has its own positive and negative effects on soil parameters such as bulk density, bulk density, soil structure, bulk density, soil pH, soil organisms, and water holding capacity.
Tarkowska *et al.* (2018) [30] examined the impacts of reduced/minimum tillage compared to traditional tillage on soil properties and diatom diversity in winter wheat cultivation. The two tillage systems studied were traditional (inversion) tillage (TT) and reduced (non-inversion) tillage (RT). Soil samples were collected during the growing season and at harvest, and various aspects of the soil, including its physical (bulk density, water content, and stability in water), chemical (organic carbon and pH levels), and biological characteristics, were analyzed. The findings revealed that reduced tillage led to higher levels of soil organic carbon, water content, and bulk density in the 0-5 cm and 5-10 cm soil layers compared to traditional tillage. There was an inverse relationship between wheat yields and easily correlated soil water content, soil organic carbon, and precipitation. In particular, soil organic carbon accumulation was 25% and 7% greater under the reduced tillage system (RT) than under traditional tillage (TT) at the depths of 0-5 cm and 5-10 cm, respectively.
Sitaula *et al.* (2017) [29] evaluated the impact of conservation tillage, with expectations of improving soil physical properties, increasing soil carbon storage, and reducing fuel, labour, and machinery expenses. The study investigated the short-term effects of reduced tillage (RT) and no tillage (NT) compared to conventional tillage (CT) concerning N_2O emissions, soil structure, and the economics of cereal production. In the wetter conditions of 2014, N_2O emissions followed the order: CT > RT > NT. Conversely, in the drier conditions of 2015, the order was RT > CT > NT. It was found that NT led to economically unfavorable returns due to higher weed control costs and lower yields in both years. On the other hand, reduced tillage demonstrated the potential to enhance agricultural outcomes in terms of both agronomy and environmental benefits.
Sharma *et al*. (2016) [26] investigated that conservation tillage affects various soil properties including compaction, aggregation, hydraulic conductivity, porosity, water storage, and soil organic carbon. Soil structure significantly influences water storage and movement. There's conflicting data on how different tillage methods impact soil's physical and chemical traits. While many studies highlight positive changes from conservation tillage on soil properties, the extent of these changes relies on factors like soil type, tillage process, moisture content, and climate. In contrast to intensive tillage, no-tillage systems often exhibit reduced overall porosity, water holding capacity, soil organic carbon, and increased bulk density. Conversely, long-term research consistently supports conservation tillage as a means to boost soil organic carbon and enhance physical properties. Intensive tillage, due to its disruption of soil aggregates and aeration, can diminish soil quality. However, the influence of management on soil carbon and physical characteristics is intricate and sometimes inconsistent over shorter periods. Additionally, investigating the enduring effects of tillage and management practices spanning more than two decades on changes in soil organic carbon's physical attributes is imperative.
Rusu (2014) [24] revealed that compared to traditional soil systems, the adoption of minimal and no-tillage approaches significantly increased organic matter content from 2% to 7.6% and water-stable aggregate content from 5.6% to 9.6% at a depth of 0-30 cm. Across all minimal and no-tillage systems, there was a notable increase in water retention (12.4% to 15%), albeit with a slight increase in bulk density values (0.01% to 0.03%) – though this difference was not statistically significant. While soil fertility and wet aggregate stability were initially low, the implementation of

conservation practices had a positive impact on soil characteristics, notably enhancing water permeability. This improved the availability of soil moisture during the plant's growing season, benefiting plant hydration. Additionally, the gradual release of retained soil water helped regulate both plant water status and soil structure.

Comparison of minimum tillage practice with different tillage practices

Calcante and Oberti (2019) [3] compared three different farming methods employed in paddy rice cultivation areas in Italy. These methods included conventional tillage (CT) and two conservation-oriented approaches: minimum tillage (MT) and no-tillage (NT). Various cost factors, such as seed, fertilizer, pesticides, and fuel, as well as operating hours, were monitored for each approach throughout the entire production season in three separate experimental areas. The total production cost was determined by combining the mechanization cost, calculated according to the American Society of Agricultural and Biological Engineers (ASABE) EP 496.3 methodology, with the production cost. The study's findings revealed significant cost reductions for both minimal tillage (16%) and no-till (19%) when compared to conventional tillage.

Khan *et al.* (2017) [13] investigated the effects of various tillage methods (minimum, conventional, and deep tillage) on soil properties and the growth of maize crops. Conventional tillage was found to enhance both crop yield and leaf area index. In contrast, minimal tillage was effective in reducing nutrient leaching, particularly nitrates. Different tillage practices had varying impacts on soil properties, including soil bulk density (measured in Mg/m), particle density, soil organic carbon content (measured in g/kg), infiltration rate (measured in mm/h), percentage of porosity, and soil saturated hydraulic conductivity (measured in mm/h). The study recommended the use of minimal tillage to prevent nutrient leaching, which can lead to reduced crop productivity.

Grange *et al.* (2005) [5] studied the impact of decreasing profit margins in crop production systems and all possible options that would increase net profits need to be explored. In sugar cane cultivation, land preparation and manure disposal can be major factors influencing the overall production cost. As it was estimated that mechanization could account for up to 50% of total production costs, reducing the number of ploughing operations can potentially realize significant cost savings. However, these savings must be offset by other costs associated with minimum or no-till systems, such as an increased need for herbicides. In addition, traditional farming methods lead to reduced yields in the long term, so the introduction of minimum and no-tillage in sugarcane cultivation was expected to increase yields and reduce costs. Eight years of data from five sugarcane tillage methods were compared, and the results showed that mechanical seeding and minimum tillage with soil removal produced 29.3% and 39.4% larger economic returns than conventional tillage and no-tillage, respectively. Other minimum tillage treatments including sub-soiling and machine or manual planting combinations were also performed well.

Kandeler *et al.* (1999) [12] examined the impact of various tillage methods (conventional, minimal, and reduced) on several soil microbiological characteristics in a fine-sandy loamy Haplic Chernozem soil. The timing of soil sampling was found to have a relatively minor influence on microbial biomass and soil microbial activities compared to the type of tillage used. However, significant treatment effects on microbial biomass, nitrogen mineralization, and potential nitrification became apparent after a 4-year period. In the initial year of the experiment, xylanase activity was notably higher in the 0 to 10-cm soil layer of the reduced and minimum tillage systems, followed by increased protease and phosphatase activities in the second year. The slower response of substrate-induced respiration to changes in tillage types was attributed to differences in biomass carbon turnover rates. After four years, it was determined that the stratification of soil microbial biomass within the profile of reduced and minimum tillage systems likely contributed to more active soil microbial activities near the soil surface.

Horne *et al.* (1992) [8] investigated the effects of three tillage methods – zero tillage, minimum tillage, and full tillage using a mould board plough – on the properties of a fine-textured, imperfectly drained, loess soil under a maize/oats rotation. This assessment was conducted after 10 years of continuous cropping and was compared with an adjacent pasture site. Zero tillage resulted in higher soil bulk densities and larger soil aggregates, while also reducing total porosity compared to full and minimum tillage methods. Interestingly, the saturated hydraulic conductivity of soil cores from the top 100 mm of each tillage treatment, just before seedbed preparation, showed no significant changes. In terms of water infiltration rates, full and minimum tillage methods had higher rates compared to zero tillage. The study also used wet sieving to assess aggregate stability and found that continuous cropping led to a decrease in aggregate stability compared to grassland. Within the 50-250 mm layer, both minimum and zero tillage treatments increased soil strength compared to full tillage. After a decade of cropping, the soil underwent redistribution, resulting in lower carbon content and cation exchange capacity in the cropped soil, especially at the surface in the full tillage treatment, compared to nearby pasture. Different tillage methods also led to varying nutrient distribution patterns in the surface layers. For instance, phosphorus and exchangeable potassium minerals, as well as pH improvements from lime addition, were higher in the 0–50 mm depth under zero tillage compared to full or minimum tillage, where more soil mixing had occurred. The study suggested that minimum tillage appears to be the most suitable method for maintaining both the chemical and physical fertility of the soil when practicing continuous cropping on this particular soil.

Effect of minimum tillage practice on energy efficiency

Mitchell *et al.* (2004) [19] revealed that while the short-term impact on production was minimal, the benefits of minimum tillage might include lower fuel usage, decreased labor, increased storage of active carbon in surface soils, and less potential nitrate leaching. However, potential disadvantages of minimum tillage may have an impact on producers' decisions to use permanent-bed systems or minimum tillage over extended periods of time. These negative effects include somewhat reduced yields, probable disease issues, and the requirement to supplement fertilizer to make up for decreased crop nitrogen and phosphorus levels. Despite these issues, using minimum tillage alternately with conventional tillage may nevertheless yield long-term financial and environmental advantages. According to research, tillage activities in the cultivation of vegetables often involve high time, energy, equipment, and labour expenses that frequently account for more than 25% of total pre-harvest production expenditures. diverse set of reduced-tillage or minimum-tillage methods for vegetable production have demonstrated effectiveness in reducing expenses and enhancing soil management. These approaches were developed and effectively implemented in the Central and Salinas Valleys for cultivating various vegetable crops. The primary objectives behind creating these systems were to reduce production costs and minimize the duration needed for soil preparation between crop cycles or for introducing a cover crop during the winter.

Rusu (2014) [24] assessed the energy efficiency, productivity and soil conservation potential of different soil tillage systems. It found that minimum tillage and no-tillage systems offered viable alternatives to conventional ploughing in terms of soil conservation and crop production. For instance, these systems produced maize at 96%-98% (minimum tillage) and 99.8% (no-till) of the yield achieved by conventional tillage. Similarly, for soybeans, the yields were 103%-112% (minimum tillage) and 117% (no-till) of conventional tillage, and for wheat, the yields were 93%-97% (minimum tillage) and 117% (no-till) of conventional tillage. Choosing the appropriate tillage system for crop rotation can help reduce energy consumption. For example, maize had an energy consumption of 97%-98% of conventional tillage when using minimum tillage and 91% when using no-tillage. Similarly, soybeans had an energy consumption of 98% (minimum tillage) and 92% (no-tillage) of conventional tillage. Energy efficiency, in this context, refers to both reduced energy consumption and the effectiveness of the tillage technique on crop growth. The study found that energy efficiency, measured as energy generated per MJ utilized, was highest for all crops in the rotation under no-tillage: 10.44 MJ/ha for maize, 6.49 MJ/ha for soybeans, and 5.66 MJ/ha for wheat. In addition to comparing energy generated, energy spent, and energy yield, a comprehensive assessment of energy efficiency in agricultural systems must consider the soil's energy efficiency and its impact on soil conservation. Only then can agricultural systems be considered sustainable from agronomic, economic, and environmental perspectives.

Sijtsma *et al.* (1998) [28] conducted two studies to assess the cost of tillage in eastern Canadian regions. In the first study, on sandy loam Podzolic soil in Prince Edward Island, fuel consumption and tractor drawbar energy were calculated for specific tillage equipment and minimum tillage. In the second study, they examined alternative minimum tillage methods suitable for Atlantic Canada in the context of a 360-hectare farm with a three-year crop rotation involving potatoes, barley, fodder, and soybeans. The average daily fuel consumption for seedbed preparation and crop establishment was found to be lower for several minimum tillage practices (ranging from 10.0 to 23.7 liters/ha) compared to traditional mouldboard ploughing (27.6 liters/ha). Tractor drawbar energy was also lower for minimum tillage (53.3–127.3 MJ/ha) compared to conventional mouldboard ploughing (140.4 MJ/ha). To determine cost differences in tillage scenarios for both rotations, the study considered anticipated changes in equipment capital costs and total operating costs. In both crop rotations, conventional mouldboard ploughing with secondary tillage proved to be the most expensive tillage method. For the three-year potato rotation, replacing the mouldboard plough with various combinations of alternative tillage methods (such as chisel plough, disc harrow, and power harrow) resulted in annual tillage cost savings of 44-60% and 10-40%, respectively. This suggests that adopting different minimum tillage practices would be more cost-effective than the traditional mould board ploughing method, assuming that tillage is the only variable input cost (i.e., without considering potential yield penalties or variations in other input costs).

Ozturk *et al.* (2008) [22] investigated the energy requirements for producing second-crop maize using four different tillage systems: minimal tillage with stubble (MTS), minimum tillage without stubble (MT), conventional tillage with stubble (CTS), and conventional tillage without stubble (CT). These tillage systems were applied after the wheat harvest, with maize planted as the subsequent crop. Various inputs, including machinery, fertilizers, seeds, irrigation, and chemicals, were considered as both direct and indirect energy inputs, and their energy consumption was quantified. When minimum tillage (MT) was employed instead of conventional tillage with stubble (CTS), there was a notable reduction of 53.7% in energy inputs related to fuel and machinery used for the tillage operation. Specifically, the total energy input required for growing maize with conventional tillage including stubble (CTS) amounted to 20,608 MJ/ha, whereas using minimum tillage (MT) reduced this energy requirement to 19,102 MJ/ha.

Conclusion

By enhancing crop output, minimizing soil erosion, preserving moisture, and boosting soil health, minimum tillage practices have the potential to revolutionize modern agriculture. The strategy is economical, cost-effective, and may help farmers save a lot of revenue over the long run.

The ability to take up new skills and adjust to new agricultural techniques is essential for the effective adoption of minimum tillage practices. Farmers may profit from minimum tillage methods and help ensure a more sustainable future for agriculture by using correct planning, crop management, and soil conservation practices.

Even while minimum tillage methods have numerous advantages, there may also be some disadvantages. There may be some initial yield decreases while the soil gets used to the new farming technique, and the method may not be appropriate for all crops. However, with the right planning, crop rotation, and soil management techniques, these disadvantages may be reduced.

A mindset of change and an interest to modify conventional farming methods are requirements for the adoption of minimum tillage practices. Farmers who desire to utilize minimum tillage must be prepared to make investments in new machinery and technology as well as go through training.

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