



REVIEW ARTICLE

Soil swapping under the CVR approach: A novel strategy for restoring soil health and ecological resilience

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Abstract

Globally, soils are increasingly subjected to severe degradation due to both natural and anthropogenic factors, including climate change, urbanisation, deforestation, soil erosion and salinisation. The resulting decline in soil quality across many farming systems has intensified the need for sustainable pathways that can restore soil physical, chemical and biological functions while minimising external inputs. One such emerging practice is the soil swapping technique developed by farmer Chintala Venkata Reddy (CVR), in which mineral-rich subsoil is exchanged with degraded topsoil layers. This process is believed to activate latent microbial populations, release mineral-bound nutrients and alter soil particle distribution by exposing deeper layers to oxygen and biological activity. Collectively, these changes improve soil porosity, moisture retention and nutrient cycling. Field-level observations and preliminary evaluations have reported enhanced crop performance, improved nutrient-use efficiency and reduced fertiliser requirements across various cropping systems. These findings are partially supported by studies on subsoil amelioration. However, the technique also raises concerns, including the disturbance of natural soil horizons and the potential spread of weeds and soil-borne pathogens. Due to the lack of long-term experimental datasets and uncertainties associated with field-level implementation, robust scientific evidence remains limited. To better understand and validate this approach, further research is required, including monitoring changes in soil organic carbon (SOC), analysing shifts in microbial communities, identifying mineral release patterns, evaluating soil-type specificity and assessing environmental risks. Overall, the CVR method represents an innovative and cost-effective strategy with potential relevance for smallholder-based regenerative agriculture. However, comprehensive multi-location trials, assessments of soil biochemical functions, economic risk analyses and multi-season crop response studies are essential to establish its agronomic and ecological sustainability. This review is based on a synthesis of published scientific literature, field observations and farmer-based reports and it highlights current knowledge, underlying mechanisms and key research gaps related to the CVR soil swapping method.

Keywords: carbon sequestration; CVR technique; nutrient cycling; soil health; soil swapping

Introduction

Among the major environmental challenges, soil degradation stands out as one of the most critical threats to global food security, ecosystem integrity and sustained agricultural productivity. Conventional agriculture, characterised by excessive tillage, nutrient mining, crop residue burning and unsustainable land management practices, has hastened the decline of soil organic matter, reduced aggregate stability and disrupted nutrient cycling across various agroecosystems globally (1). The progressive reduction in the capacity of soils to sustain crop production, along with their reduced resilience, is a combined effect of deteriorating soil health and stresses induced and intensified by climate change (2). According to global assessments, nearly one-third of the world's soils are subjected to moderate to severe degradation due to declines in soil organic carbon (SOC), salt intrusion and chemical degradation (3). Similarly, in India, about 146.8 million hectares of land are affected by soil degradation (NBSSLUP, 2004) due to intense cropping, imbalanced fertiliser application, shortened fallow periods and limited adoption of restorative soil management practices. Assessments of soils nationwide indicate areas with deficiencies in SOC, along with major and micronutrients (N, K, B and Fe), particularly in dryland farming zones that account for a major share of India's food production (4). Carbon sequestration potential is often quantified in terms of SOC, which is a key indicator of soil health. However, the rapid loss of SOC poses a long-term threat to both food production and a country's commitment to mitigating climate change. In this context, regenerative methods that are cheap, scalable and easy for farmers to use are urgently needed. Such methods should be capable of rebuilding soil organic matter, improving nutrient-use efficiency and restoring degraded areas without increasing production costs for farmers. Common methods for restoring soil, such as biochar production, large-scale composting and integrated nutrient management, work well but are often limited by high costs, the complexity of their use, or the small supply of biomass. Therefore, new tools that make it easier for small and struggling farms to help their soil recover are very useful. One new idea that has recently emerged is the soil rejuvenation approach developed by Chintala Venkata Reddy (CVR). Chintala Venkata Reddy, an experimental farmer from Telangana, India, developed this soil management approach through decades of on-farm observations and experimentation. The approach aims to improve soil quality, nutrient-use efficiency and crop resilience and has subsequently gained recognition among researchers and policymakers. This method suggests a simple and cheap way to improve soil functional characteristics and SOC levels. The technique is based on the idea that targeted amendments and enhanced microbial activity can speed up the stabilisation of organic matter in the soil. This makes the soil structure, nutrient retention and biological activity improve faster. This farmer-driven and practice-oriented strategy has considerable potential for widespread use, especially in areas with few resources where traditional restoration methods are too expensive. It is important to scientifically evaluate such grassroots inventions to see how well they work for farming, how they help the environment and how they might help with long-term soil management. This review synthesises the available documentation on the soil swapping practices developed by Chintala Venkat Reddy, including evidence from patents, reports from state and central agricultural institutions and observations from farmer field trials, to understand their adoption and reported outcomes under field conditions. It also examines the effects of this

practice on the relocation of nutrient-rich subsoil, the rearrangement of soil horizons and the use of soil-derived inputs on soil physical, chemical and biological functions, interpreted through established principles of soil science and plant physiology. Furthermore, the review identifies future research gaps and highlights the lacunae of the study, including multi-season on-farm assessments, combined analyses of soil properties, SOC dynamics, pest suppression mechanisms and potential broader regenerative agriculture strategies.

Methodology

The methodology of CVR focuses on sustainable soil rejuvenation and natural biofortification. First, depleted topsoil is restored by excavating mineral-rich subsoil from a depth of 1–1.5 m and blending it into the cultivation layer. For pest management, a "soil spray" is prepared by mixing 15 kg of dried subsoil with 200 L of water, using the filtered supernatant as a foliar application (Fig. 1). This silica-rich solution acts as a physical deterrent against pests like the fall armyworm. Additionally, crop nutritional value is enhanced through the application of organic precursors—specifically carrot and sweet potato extracts—during the flowering stage. This process naturally biofortifies grains with high levels of Vitamin D and Vitamin A. The effectiveness is validated through comparative soil health analysis and mass spectrometry of the harvested produce. These patented techniques significantly reduce reliance on synthetic fertilisers and chemical pesticides.

Concept and development of the CVR soil swapping technique

History and evolution of the soil swapping idea

Severe urbanisation and global climate change have paved the way for soil degradation, leading to the erosion of nutrient-rich soil and further depletion of crop yields. Gradually becoming aware of these challenges, CVR came up with the idea of soil swapping i.e., interchanging degraded topsoil with nutrient- and moisture-rich deeper soil layers. He started his experimentation by digging narrow trenches, excavating soil, sun-drying the excavated material and distributing it in thin layers across the field. Following such interchanging over the seasons, he noticed improvements in crop growth and yield parameters, such as crop vigour, stout tillering and enhanced grain quality, compared to conventional methods, which further pushed him to expand his innovative trials to cereal crops such as rice and wheat. This approach started as a seed and gradually matured into a fruitful idea, catching the attention of policymakers and nationwide recognition started spreading through formal documentation. Several patent filings described subsoil excavation, restoration of soil profile and preparation of soil-based sprays. Subsequent patents detailed additional applications, including nutrient enhancement and natural pest suppression.

Adoption in Telangana and other regions

As he was born and brought up in Telangana, his practices were rooted in the soil of Telangana, which inspired neighbouring farmers to begin this practice on their own lands. Several ICAR institutes, such as ICAR-IIMR, ICAR-IIRR and ICAR-DOR, along with state agricultural universities, started guiding farmers on this technique, its implementation and its benefits. Due to its low-cost and eco-friendly approach, this practice gained widespread importance within a short time. Owing to severe pest pressures,

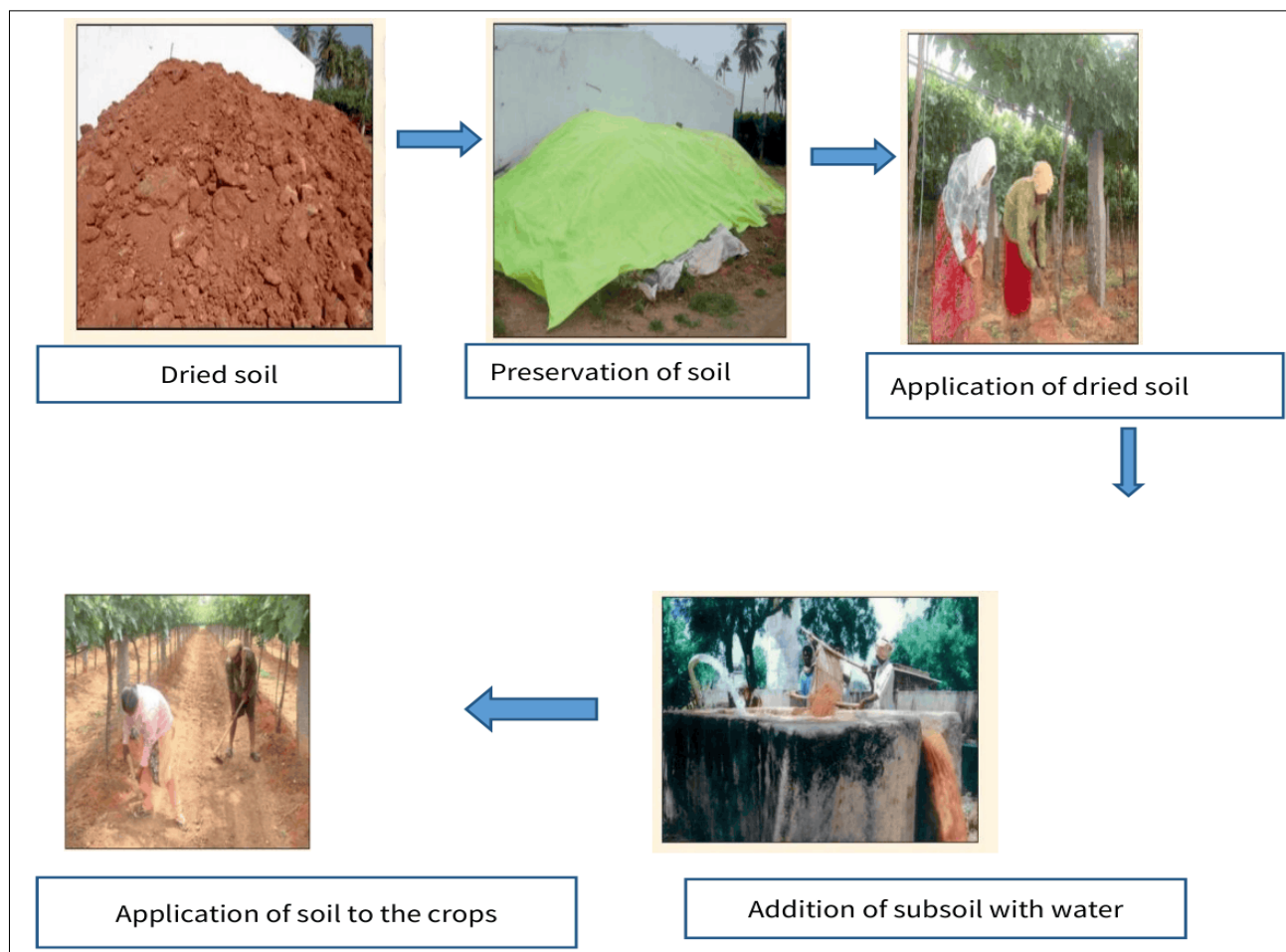


Fig. 1. Application procedure of CVR technology.

such as locust swarms and armyworm infestations, farmers in neighbouring states came across this approach through local media reports highlighting its benefits and they started implementing this technique either as an alternative to chemical treatments or as a supportive measure alongside them. Although uptake has varied and has largely spread through informal farmer-to-farmer channels, the method has come to be viewed as an affordable option within regenerative farming practices. Scientific evaluation across different agro-ecological zones is still progressing, yet the technique continues to feature prominently in discussions on soil restoration and sustainable agriculture in several states.

Possible mechanisms of soil improvement

Soil profile and horizons

A soil profile consists of a sequence of natural layers, or horizons, arranged vertically from the surface downward, each having its own physical, chemical and biological traits (Fig. 2). The uppermost layer, the O horizon, is composed mainly of organic matter in areas where there is a large accumulation of fallen leaves, twigs, decomposed roots and other biological debris. Such accumulations occur in forested landscapes, wetlands and ecosystems with cool or moist climates that slow decomposition. With increasing depth, the layer starts changing the colour from light (surface) to dark black (humus) due to its high carbon content and profound biological activity. This layer plays a key role in moisture retention, nutrient cycling and supporting soil fauna (fungi, insects and microorganisms). In agricultural lands, this horizon may even be absent due to tillage and residue removal. Next comes the topsoil, named the A horizon which is generally present in agricultural fields. With proper management, it contains

the highest levels of organic matter and supports most root growth due to its fertility and intense biological activity. Beneath this lies the subsoil, named the B horizon, where materials such as clay, iron and aluminium compounds often accumulate, making it denser and less biologically active than topmost layer. Next lies the C horizon, where the soil starts to merge with the underlying geological material. Due to this, there is less biological activity and its structure is often coarse and irregular. Collectively called the regolith (A + B + C), it plays an important role in long-term soil development, as the gradual weathering of this material continuously supplies minerals to the layers above.

Microbial activation

Microbes reside deep within soil layers in oxygen-deprived horizons. When these layers are exposed at the surface through the soil swapping technique, it awakens dormant microbes, which further plays a proactive role in mineralisation of organic matter due to strengthened physical conditions such as oxygen availability and sunlight (5). The procedure is depicted in detail in Fig. 2. Previously oxygen-deprived soil layers exposed to air generate microbial enzymes more quickly, carbon compounds break down at a faster pace and microbial populations expand sharply (6). Likewise, microorganisms present in deeper soil layers often include hardy groups that can respond quickly once they receive oxygen and fresh organic inputs (7). Together, these findings suggest that soil swapping can stimulate nutrient turnover and reinforce the soil's biological buffering capacity, contributing to improved soil functioning and greater resilience.

Mineral release and nutrient cycling

Greater quantities of minerals tend to accumulate in deeper

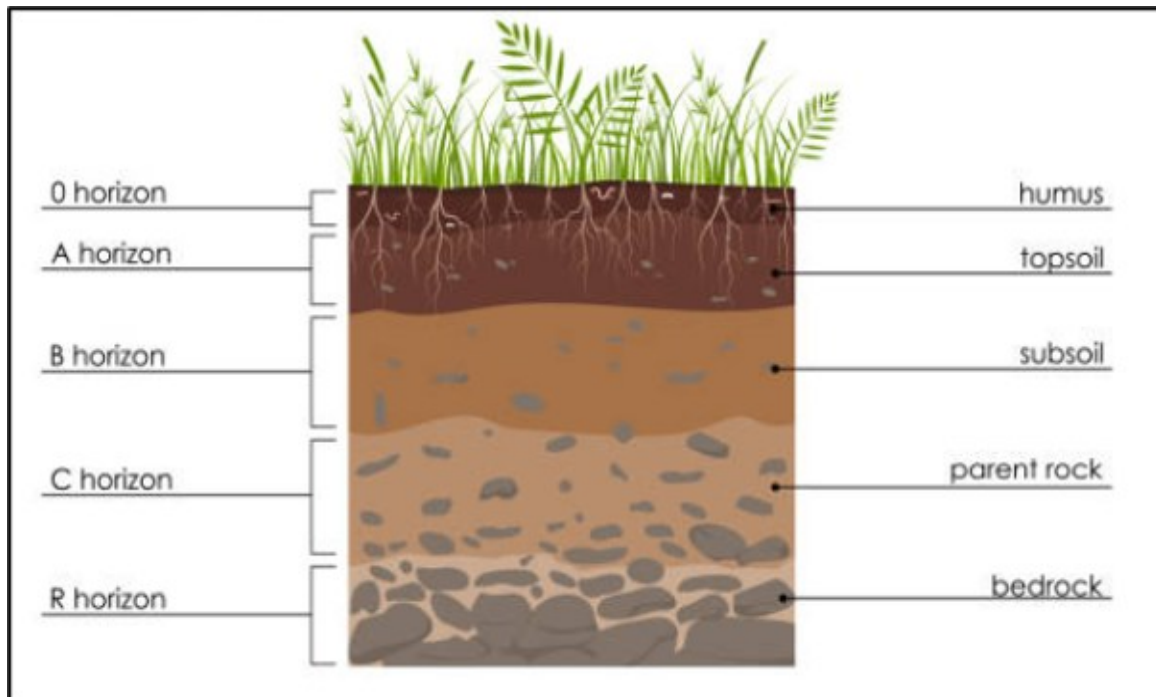


Fig. 2. Visual representation of soil horizons.

subsoils that remain inaccessible to plant roots and aerobic microbes (Fig. 3). By means of soil swapping when these deeper horizons are brought to the surface, disintegration of minerals tends to occur due to active and passive factors and renewed microbial activity accelerates the weathering of primary minerals, releasing nutrients such as N, P and K, along with secondary minerals (Ca, Mg and S) and micronutrients (Fe, S, Zn, B and Mo). Further, under aerated conditions, when freshly exposed mineral surfaces undergo weathering, silicon and other cations become highly available (8). Minerals containing iron and magnesium tend to weather more quickly when microbial activity increases and oxygen becomes more available, leading to greater release of

micronutrients essential for plant metabolism (9). The influence of revived microbial communities on mineral breakdown has also been highlighted in a previous study, which showed that both bacteria and fungi can speed up the decomposition of silicate and sulfide minerals, thereby improving the availability of elements such as zinc, boron and molybdenum (10). Taken together, these processes indicate that soil swapping can support a more continuous nutrient supply, strengthen soil fertility and enhance the overall resilience of cropping systems.

Soil physical improvements

Inversion of soil horizons tends to improve physical soil properties such as, bulk density, porosity, water infiltration and deeper root

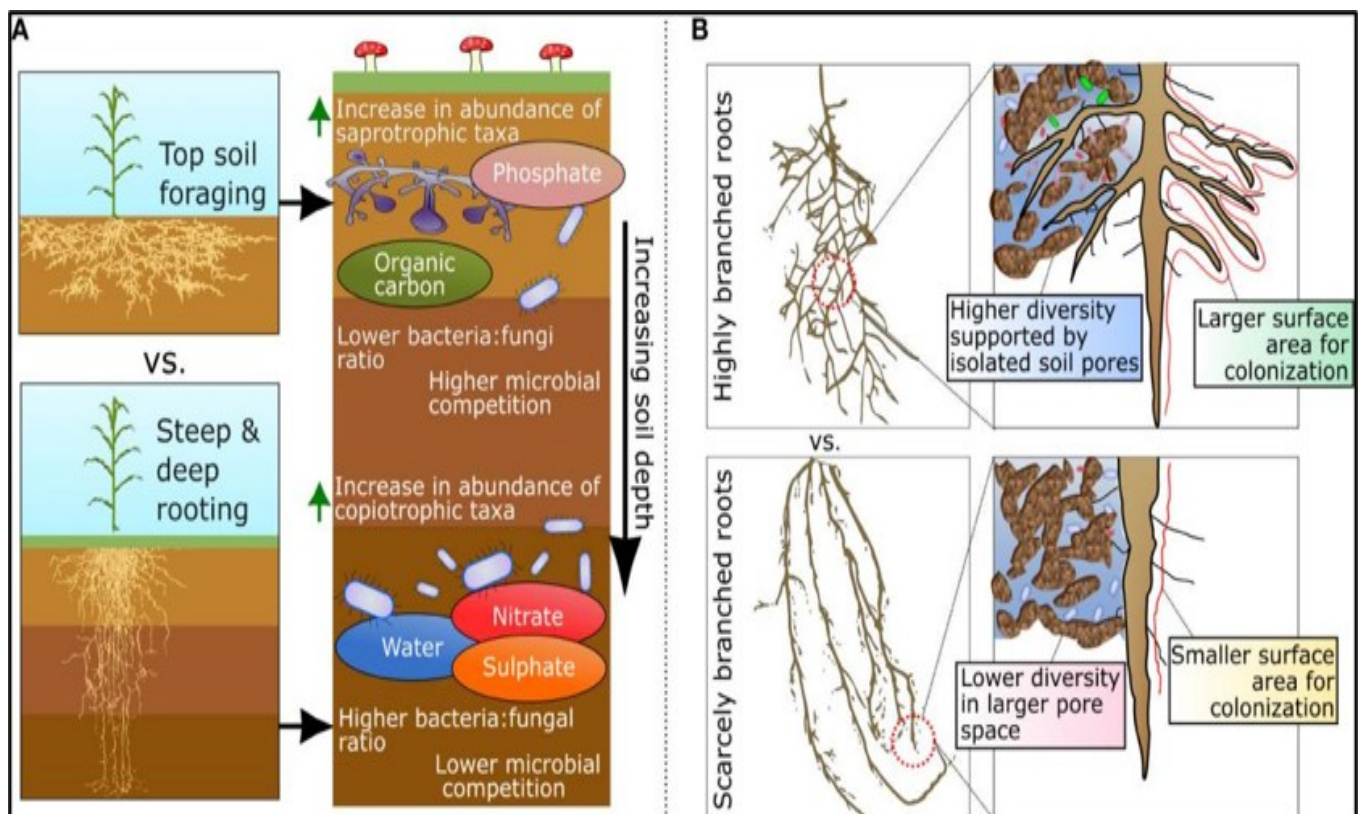


Fig. 3. Microbial and nutrient release patterns in topsoil versus subsoil.

penetration. When surface layers are conjoined with compacted subsurface layers, they are exposed to weathering (biological and physical) and their structure gradually loosens, resulting in measurable reductions in bulk density. Due to the soil swapping technique, soil aeration is improved due to diminished mechanical resistance and further promotes a suitable environment for root growth and elongation (11). When nutrient-rich subsoil gets exposed through the CVR technique, it enhances soil porosity, along with better water entry and movement through the soil profile due to increased pore continuity (12). Similarly, the CVR technique leads to enhanced macropore formation that further improves infiltration rates and provides a path for deeper penetration of plant roots in revitalised soils (13). All the above-mentioned changes collectively augment improved interactions between soil and plant, increase resistance to drought and soil compaction and maintain the long-term health of the soil under a variety of cropping systems.

Chemical properties

The process of soil swapping causes observable changes in the chemical environment of the soil profile, in particular through alterations in pH, electrical conductivity (EC) and the behaviour of organic carbon. When subsoil layers that are frequently more alkaline or acidic than the surface horizon are exposed, the mixing of different soil constituents results in a progressive adjustment of soil pH. This adjustment is driven by the dissolution of carbonates, the creation of organic acids and the enhancement of microbial respiration. Through the process of soil swapping, modest adjustments in aeration and moisture levels within the soil were observed. This, in turn, led to an increase in the carbonate equilibrium, which ultimately resulted in a neutral pH range where the availability of nutrients to plants was increased (14). Disrupting the deeper soil layers may cause a minor increase in soil EC, possibly due to the movement of soluble salts. However, this increase in salt concentration is balanced out by regular leaching, which may release mineral-bound ions (15). Combining carbon-poor subsoil with carbon-rich, proactive topsoil had a similar effect on organic carbon dynamics as soil EC by encouraging both carbon mineralisation and novel pathways for carbon stabilisation. Microbes that were dormant become active and start oxidising leftover carbon when they obtain more oxygen. This also creates organo-mineral complexes that can help store carbon for a long time (16). In general, these processes show that soil swapping changes the chemical characteristics of the soil in ways that affect nutrient cycling, soil structure and how the ecosystem works as a whole.

Agronomic and ecological implications

Implementation procedure

The success of any new technique relies on its application in a real-world environment; similarly, practising the soil swapping technique requires systematic field preparation, followed by methods to excavate subsoil and an understanding of the soil chemical functions that influence soil properties. The implementation process of CVR is depicted in Fig. 4. The first step begins with clearing the stubbles of the previous crop, determining soil compaction and marking suitable points to excavate the soil. Prior examination of hardpan layers improves the effectiveness of deep-soil interventions (17). The next step was field levelling under optimum moisture conditions, followed by marking soil swapping points in the 20–60 cm layer where nutrient-rich or dormant-microbe zones existed. These depths were preferred due to the fact

that they often contained organic matter that was not available to plants; however, once these layers were interchanged, unweathered nutrient reserves might become biologically active under surface-enriched conditions (moisture and oxygen). The choice of tools largely depends on the size of the farm. In smallholdings, farmers generally rely on simple implements such as spades, hand augers and the traditional country plough to expose and lift pockets of subsoil. In contrast, medium and large farms make use of more mechanised options like mini-excavators, post-hole diggers, tractor-mounted augers and trenchers to carry out the same work more efficiently. Using these tools according to farm size creates mechanical disturbance to the soil at particular depths but no excessive degradation of soil structure, making them game changers (18). After subsoil excavation, it was intermixed with the addition of organic inputs such as green manure residues, compost and farmyard manure, which further enhance soil aggregation along with microbial activation to release nutrients from mineral-bound soils. Further, this promotes humus formation in the long run, which acts as a storehouse for nutrients (19). Among different methods of soil swapping, the partial swapping approach lifts limited portions of subsoil at intervals across the field, ensuring that the overall soil profile is not heavily disturbed. This pattern of small, distributed interventions resembles localised inversion practices (20). In rainfed regions, CVR soil swapping method, is based on trenches, which requires digging narrow channels (30–60 cm deep) at regular intervals to expose the subsoil and make room for organic inputs along the crop line. Farmers use the pit method to make individual pits, bring the deeper soil to the top and mix it with organic resources. A number of studies have shown that this kind of pit excavation can help store more moisture and help roots develop better in dryland farming (21). These variations created by farmers show how soil swapping may be used in diverse production settings. They are a cheap solution to boost biological activity and enhance nutrient availability.

Field application procedures

When excavating, over 1 kg of subsoil needs to be dried and fed straight to the drip emitter at regular intervals for high-value and perennial horticultural crops (Fig. 4). The drip method was chosen because it delivers water and nutrients exactly where they are needed, which makes nutrients and moisture more available, improves root metabolism and ensures that nutrients are released from the soil at the same time as water is supplied to the crops. In flood-irrigated crops, such as rice fields, this method must be used after the standing water has been removed. Then, dry subsoil or topsoil is mixed with irrigation water or water drums so that the nutrient-rich soil particles dissolve and deliver nutrients evenly to the plants. Farmers mix dried subsoil into irrigation tanks or field channels at different phases of crop growth so that the crops receive small amounts of nutrients over time instead of one large dose. This staggered supplementation helps maintain stable growth and prevents nutritional deficiencies during important phases of development. The topsoil taken from the mid-lane portion of the field, often noted for its distinct physical and chemical attributes, is preserved and later applied near the drip zone. Growers report that this material contributes to improved sweetness, aroma and overall productivity, particularly in fruit-bearing crops.

Supporting observations or experimental evidence

After successful implementation and field application of this

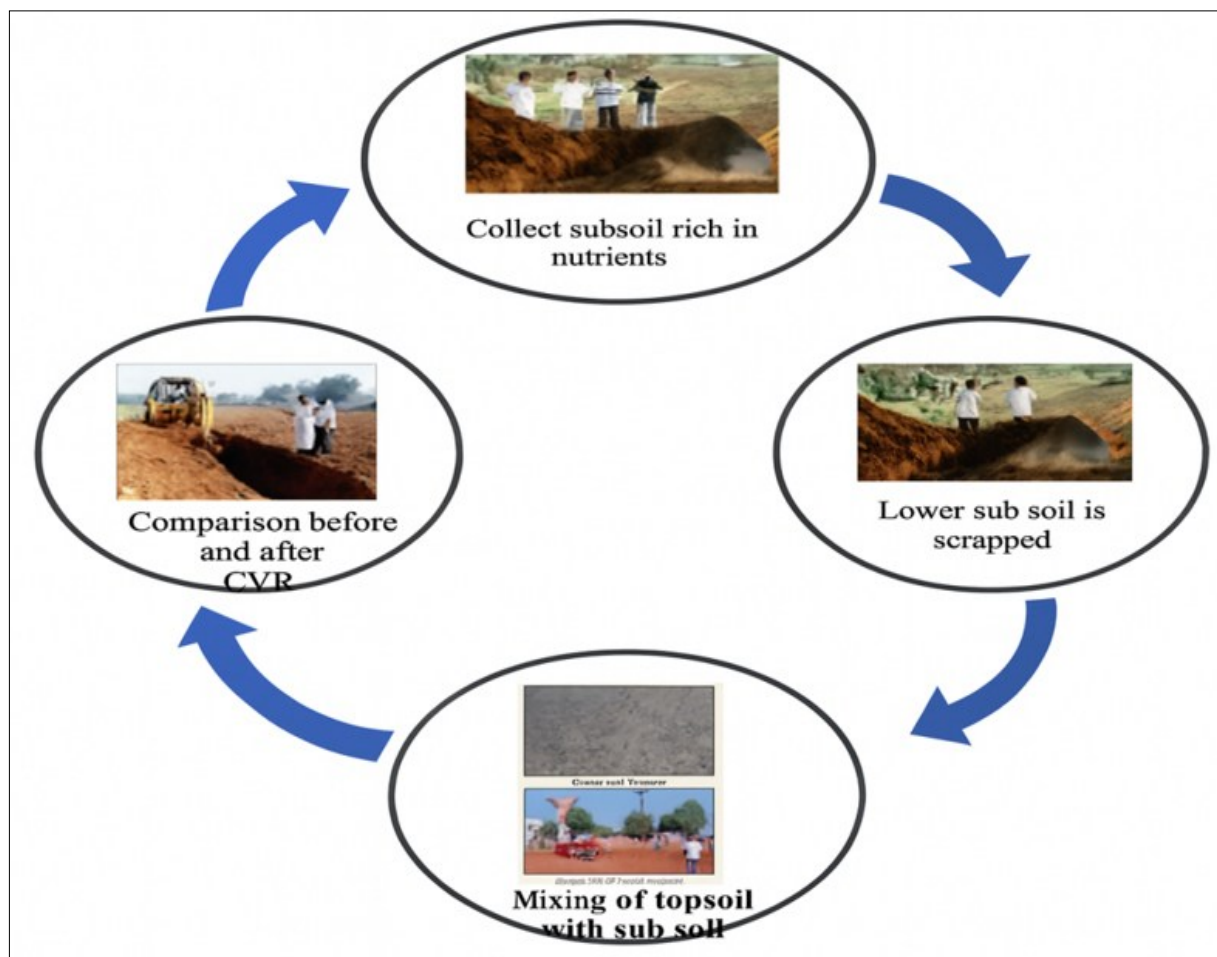


Fig. 4. Implementation procedure of CVR soil swapping.

technique, the results are discussed in the subheadings below.

Crop-wise responses to CVR soil swapping

Responses of the major cereal crop rice to CVR soil swapping depend on how interchanged layers modify surface texture, infiltration and percolation (Table 1). Exchanging soil textures, i.e., mixing sandy soils with low nutrient- and moisture-holding capacity with clay soils, can improve nutrient and moisture retention along with drainage. These outcomes were consistent with findings from inversion and deep-tillage studies (22, 23). In contrast, adding tiny (sandy) materials to clay soils may accelerate anaerobiosis or salt accumulation, as soil-mixing changes redox behaviour and N cycling (23). Benefits of soil swapping in rice crops vary with water impounding, percolation and nutrient fluxes in different locations. Maize, being a deep-rooted crop, benefits from soil swapping as it evades soil compaction and hard pans, making conditions favourable for root penetration, water and nutrient extraction and microbial mineralisation of humus (24). Research that breaks up compact or dense soil layers has shown improvements in root penetration and biomass production, indicating that CVR practices can be especially effective in fields where plough pans or hard-setting horizons limit maize growth. Benefits of soil swapping in pulse crops are tremendous, i.e., better

access to soil-bound phosphorous and improved nodulation have been observed due to conditions created by evading hard pans, which minimise soil resistance and further promote taproot growth (25). CVR soil swapping benefits pulse crops on compacted hard soils by minimally disrupting soil arrangement, mainly due to the fact that N fixation is hosted by microbes residing in the nodules of tap-rooted pulses and the process of N fixation is sensitive to oxygen (26). Improvement in seedbed structure, nutrient availability and the level of microbial activity has also been observed (27). Along with its benefits, soil transfer may increase the probability of disease spread (pathogens, nematodes), pest spread and weed invasion (28). Adoption of CVR techniques requires strict phytosanitary measures, apart from gains in crop vigour and crop yield. As the technique started with grape, a perennial fruit crop, long-term gains were observed (29, 30), which might be due to enhanced pore volume, greater scope for root penetration and higher yields obtained per unit of water used. Studies involving alterations to deeper soil layers have shown improvements in drought tolerance and more continuous nutrient uptake. While many field reports point to favourable responses under CVR practices, controlled trials in orchard crops are still scarce, underscoring the need for long-term assessments in perennial systems.

Table 1. Crop-wise agronomic responses to CVR technology based on field observations and reported studies

Crop type	Observed effect of CVR technology	Key references
Paddy	Improved root development, better tillering, 8–12 % yield increase	22, 23
Maize	Enhanced cob size, uniform growth, 10 % higher grain yield	24
Red gram	Increased pod number, improved plant vigour, 7–9 % yield gain	25, 26
Cotton	Better boll formation, enhanced fibre quality, 8 % higher yield	27
Vegetables	Enhanced root and shoot growth, 10–15 % yield improvement	28
Fruit crops	Improved fruit set and size, better flowering, 8–12 % yield increase	29, 30

Soil health improvements under CVR technology

Soil health improvements under the CVR soil restoration technology have been widely observed across diverse cropping systems, with evidence indicating notable gains in physical, chemical and biological soil quality within relatively short periods of implementation (Table 2). The main functions of the technology –keeping topsoil, aerating and sun-drying subsoil, reintegrating mineral layers and stimulating microbial activity–work together to restore aggregate stability, increase porosity and lower bulk density (31). This makes it easier for roots to penetrate and for water to flow through the soil. These results are in line with the idea that "restoring aggregate hierarchy is fundamental to soil function", which states that microbial binding agents control structural resilience (32, 33).

Mixing organic inputs with subsoil accelerates the activity of dormant microbes residing in soil and stable carbon that was in organic form starts converting to labile carbon that becomes available to plants. Alongside, primary nutrients (N, P and K) and micronutrients, which play key roles in plant metabolism, start to increase in availability (33). Due to soil interchanging, soil biological functions start to upgrade i.e., higher soil microbial biomass carbon (SMBC) and plenty of N fixers (*Rhizobium*, *Azorhizobium*, *Bradyrhizobium* spp., etc) and P fixers (VAM) become active in nutrient mobilisation, along with higher enzyme activities (phosphatase, dehydrogenase and β -glucosidase) (34). Changes in soil hydrological properties include better water retention and improved water entry into soil, along with the role of carbon-rich layers in water regulation. Considering all the above changes, the CVR technique contributes to enhanced plant mineral uptake, a robust root system and more resilient yields under severe stress in agricultural ecosystems governed by soil health (35). Overall, the CVR technique, a farmer-innovated pathway, offers a cost-effective means of recovering degraded soils.

Farmer-reported yield and economics

The CVR soil rejuvenation technique was adopted by many farmers in India across states such as Karnataka, Telangana and Andhra Pradesh and reported a range of improvements in crop performance in terms of yield (10–28 % higher) and farm profitability, attributed to better soil physical, chemical and biological health in major field crops such as paddy, red gram, cotton, maize and vegetable systems, as mentioned in Table 3. Farmers revealed that these gains were due to the increased space created for rooting, better soil moisture and a declined incidence of nutrient-related stress. Lower input costs of inorganic fertilisers (20–30 % less) were demonstrated in fields implementing the CVR technique due to the steady release of nutrients, particularly N and P. It has been reported that cumulative soil biological processes can reduce the marginal requirement for synthetic fertilisers (36). When

the soil becomes biologically rich in nutrients there is a reduced load on farmers in terms of operating costs for tillage equipment due to good soil friability. Financial analyses from case studies of farmers implementing the CVR technique show that the B:C ratio elevated by 0.20–0.45 points, mainly because stable yields are gained even under irregular monsoon conditions due to soil resilience against climatic variability (37). The financial growth and outcomes under CVR were in line with practices observed in regenerative and soil-carbon-enhancing systems globally, where improved microbial functioning and regained soil structure directly translate into higher factor productivity and net returns. Overall, farmer-reported evidence suggests that CVR technology not only restores degraded soils but also strengthens the economic viability of smallholder agriculture by lowering input dependency and stabilising yield performance.

Advantages of CVR subsoil-based pest suppression

The CVR subsoil-based methodology exemplifies an environmentally sustainable pest management technique consistent with the Lifestyle for Environment (LiFE) paradigm. Subsoil horizons generally lack active insect populations due to insufficient organic substrates and adverse microclimatic conditions, rendering them intrinsically unsuitable for pest survival (38). Subsoil suspensions sprayed onto crop canopies serve as a physical and behavioural deterrent, impeding the oviposition and feeding behaviours of insect pests. Prior research has shown that tiny mineral particles may hinder insect respiration, movement and egg adhesion, thereby diminishing pest establishment without dependence on synthetic pesticides (39). The effectiveness of clay-rich subsoil in inhibiting migratory pests such as locusts and armyworms is due to its abrasive and desiccating characteristics, which negatively impact cuticular integrity and viability (40). Furthermore, the topical application of subsoil with elevated clay content on livestock has been documented to diminish infestations of hematophagous insects, such as flies and mosquitoes, by creating a protective mineral barrier that disrupts biting and host detection (41). These mechanisms collectively underscore the promise of CVR subsurface application as a low-input, farmer-led and ecologically friendly alternative for integrated pest management within a sustainable agricultural framework. The CVR technique has been compared with other techniques in Table 4.

Benefits of the CVR soil swapping technique

Low-cost and farmer-driven implementation

Chintala Venkata Reddy's core operations, which include excavating and redistributing native subsoil/topsoil and using the resulting slurries or soil layers as field amendments, require simple tools and local labour rather than costly chemical inputs or sophisticated machinery; this makes the practice attractive to smallholders seeking affordable soil restoration options (42).

Table 2. Evidence of soil quality enhancement under the CVR soil restoration method

Parameter	Change observed	Key references
Microbial count	25–40 % increase in CFU/g soil	31
Nutrient availability	N, P, K, Ca, Mg, Fe, Zn, B, Mo increased by 10–20 %	32, 33
Water retention	15–25 % improvement in field capacity	34, 35

Table 3. Evaluation of soil swapping technique on farmers' economics

Parameter	Observed improvement	Key references
Return on investment (ROI)	12–18 % higher than conventional practice	36
Fertiliser cost reduction	15–20 % lower due to enhanced nutrient cycling	37
Yield increase (%)	8–15 % across major crops	37

Table 4. Comparison of CVR soil swapping technique with other regenerative practices

Practice	Core idea (short)	Mechanism /how it works	Main pros	Main cons	Key references
CVR / “Soil Swapping” (Chintala V. Reddy)	Excavate subsoil or transfer subsoil/topsoil, dry/mix and reapply (also subsoil extracts sprayed).	Adds different mineral fractions and micro-particles, provides micronutrients and clay fractions; foliar/soil sprays from subsoil claimed to act as nutrients/pesticide.	Low-cost, farmer-driven; reported large yield gains in farmer demonstrations; uses “soil from the soil” (no chemicals).	Mechanistic uncertainties (how long benefits persist, variability by source soil); risks of moving contaminants / changing soil biology; limited peer-reviewed field trials.	40
Natural farming	Low-input methods that harness local resources and biological processes (mulch, compost, local inputs).	Builds soil biology, organic matter and micro-ecosystem services over years.	Improved biodiversity, lower input costs, resilience in some contexts.	Often slower to show yield gains; effects depend on time, training and local context.	41
Zero budget natural farming (ZBNF)	A structured natural-farming programme using local preparations (Jeevamrutha, etc.) with government support in some regions.	Combines mulching, microbial/plant emulsions and seed/soil care to rebuild soil function.	Demonstrated biodiversity gains and improved farmer profits in large programme evaluations.	Scale-up challenges, variable short-term yields across sites; implementation fidelity matters.	42
Biochar application	Apply pyrolysed biomass (biochar) to soil.	Increases soil porosity, cation exchange, retains nutrients and water; long-term carbon sequestration potential.	Improved nutrient retention, water holding and potential carbon storage.	Effect size varies with feedstock, dose and soil type; cost and availability may limit adoption.	43, 44
Conservation tillage (reduced/no-till)	Minimise soil disturbance and retain residues.	Preserves soil structure and aggregates, increases SOC over time, reduces erosion.	Erosion reduction, improved aggregation and often better water retention.	Transition period can reduce yields in some climates; weed management needs adaptation.	45
Deep ploughing / sub-soiling (subsoil amelioration)	Mechanically break compacted layers or place amendments into subsoil.	Relieves physical constraints, improves rooting depth and access to water/nutrients; can be combined with subsoil organic amendments.	Can increase root depth and yields where hard pans exist.	Effects may be temporary; equipment-intensive and may require amendment additions; potential negative effects if done inappropriately.	46
Compost and microbial inoculants	Add stabilised organic matter and beneficial microbes (rhizobia, PGPR, mycorrhizae).	Improve nutrient cycling, build SOC and promote healthy rhizosphere; inoculants can improve nutrient uptake and stress tolerance.	Low-risk, well-understood benefits to soil organic matter and biology.	Variable performance of commercial inoculants; quality control matters.	47

Avoidance of external chemical inputs

A fundamental claim and attraction of the CVR approach is that it supplies mineral and textural amendments from within the farm landscape itself, reducing (or eliminating) reliance on manufactured fertilisers and agrochemicals; this aligns the technique with low-input, organic and regenerative paradigms. The patent and practitioner descriptions explicitly emphasise on-farm materials rather than off-farm chemicals (43).

Soil-profile rejuvenation (physical and chemical)

By relocating and mixing subsoil and topsoil layers, CVR is intended to alter the physical texture and mineral constitution of the active rooting zone, potentially improving porosity, nutrient heterogeneity and the supply of otherwise limited micronutrients. Comparable conceptual and experimental literature on subsoil amendment and deep-soil amelioration shows that such interventions can change soil physical properties and nutrient distributions in ways that improve root access and soil functioning (44).

Enhanced resilience to drought via increased water-retention capacity and improved soil structure

Field-scale and review studies indicate that amendments which increase soil organic matter, improve texture or restore degraded horizons can raise plant-available water and buffer crops during dry spells. While CVR delivers these changes by redistributing native soil fractions rather than adding external organic matter, the end result—improved pore networks and altered water-holding properties in the active root zone—is consistent with mechanisms shown to support drought resilience in multiple studies of subsoil amendments and organic inputs (45).

Co-benefits: local circularity, reduced transport/processing and potential carbon-friendly outcomes

Because CVR reuses on-farm materials rather than importing manufactured products, it supports a circular use of soil resources and may lower energy and emissions associated with input manufacture and transport. The broader literature on low-cost, locally produced amendments (biochar, compost and other on-farm innovations) shows similar sustainability advantages when correctly implemented (46).

Caveats for interpretation and research needs

Although practitioner reports and the patent indicate substantial benefits, robust, replicated trials published in high-index journals remain limited for the CVR method specifically; therefore, the advantages listed above should be regarded as mechanistically plausible and promising, but in need of systematic validation across soil types, contaminant-risk assessments and multi-season field trials. Parallel literature on subsoil amelioration and organic amendments serves as the best current empirical analogue (47).

Limitations and concerns of the technique

Suitability restricted to specific soil types

The performance of the CVR technique is highly dependent on the characteristics of the subsoil being introduced into the surface layer. Studies on horizon mixing and subsoil amendment show that outcomes vary widely across soil orders. Subsoil-based amelioration is beneficial mainly in soils with favourable mineralogy but can be ineffective or even detrimental in soils containing acidity, salinity or poor structural stability (48). The chemical quality of subsoil materials determines whether deep amendments enhance soil quality or introduce new constraints (49).

Potential disturbance of soil ecological processes when done repeatedly

Mixing topsoil with deeper horizons disrupts the natural stratification of microbial communities and organic matter distribution. Deep soil disturbance and inversion alter microbial functional groups and accelerate carbon turnover (50). Evidence from deep tillage trials reinforces this concern and earlier studies suggest temporary reductions in microbial biomass and enzyme activity following repeated soil mixing (51). These findings imply that frequent or heavy use of the CVR technique may impair biological functioning and slow ecological recovery.

Elevated risks in Vertisols (black cotton soils)

Black soils, due to their high smectite clay content and shrink-swell behaviour, are sensitive to mechanical disturbance. During crop sowing, land preparation in black cotton soils involves horizon inversion, which creates swelling pressure, instability during wet periods and promotes re-compaction (51, 52). Such soils may respond poorly to the movement of subsoil into the top horizon, making CVR inherently risky without prior soil testing. These results highlight the need for extreme caution when applying CVR in cotton-growing belts dominated by Vertisols.

Need for mechanisation and limits on how well it can work

People say that CVR is cheap, yet it requires digging up, drying, mixing and moving around vast amounts of dirt. Only small plots can be done by hand. Soil restoration methods that require deep manipulation need machinery such as augers, excavators or loaders, which may not be available in places with few resources (53). Horizon modification procedures necessitate substantial labour and energy inputs, thereby limiting application in contexts with restricted equipment availability (54).

Limited scientific literature and the need for strong validation

A significant issue is the lack of controlled, peer-reviewed scientific research solely assessing CVR. Chintala Venkata Reddy's patent (EP2272313A1) and reports from the government and the media are the main sources explaining the process. As indicated in the material assembled by Reddy (Patent, 2014) and concisely recapitulated by other reviewers, the technique lacks the substantial experimental evidence that exists for subsoil amelioration, deep placement of supplements, or carbon-enhancing regeneration techniques (55). This gap emphasises the necessity for systematic experiments assessing long-term soil health, pollutant risk, crop response and reproducibility across various soil types.

Research gaps and future directions

Research gaps

Lack of long-term, replicated field trials: There is a deficit of multi-season, replicated experiments that evaluate CVR (soil swapping) across crops, management histories and climatic regimes. Long-term datasets are essential to determine whether initial yield and soil-property responses persist, decline, or reverse over time. Annual Review work on deep soil carbon emphasises that much SOC is stored below 20 cm and responds on decadal timescales, indicating the need for long-term monitoring when altering horizons (56). Likewise, farmer-acceptance reviews show that many subsoil amelioration claims remain rooted in demonstrations rather than replicated trials (57).

Recommended action: establish multi-site, randomised block experiments with at least 3–5 years of continuous monitoring (yield, SOC, soil chemistry, rooting depth) and baseline soil surveys.

Limited data on soil biological (microbial and faunal) responses and recovery trajectories

Mixing and inverting horizons fundamentally reorganise the vertical distribution of microbes and mesofauna. Reviews and empirical studies show that soil depth structures microbial community composition and function and that bulk soil mixing can reduce bacterial richness and alter assembly processes. For CVR, there is little direct evidence documenting the magnitude, direction and timescale of microbial and faunal recovery following horizon transfer (58).

Recommended action: Pair CVR field trials with molecular (amplicon/metagenome), biochemical (enzyme activities) and mesofauna surveys sampled by depth and time (0–10, 10–30, > 30 cm) to capture recovery dynamics.

Un-quantified effects on greenhouse gas (GHG) fluxes

The net climate impact of moving subsoil into the active rooting zone is unknown. Tillage and intensive soil disturbance frequently change CO₂, N₂O and CH₄ fluxes; strategic tillage studies show both increases and decreases in net emissions depending on context and recent reviews highlight the multiplicity of drivers affecting soil GHG emissions under management change (59). There are virtually no measurements of GHG fluxes (chamber or eddy covariance) before and after CVR operations.

Recommended action: include standard GHG monitoring (static flux chambers with high-frequency sampling) in CVR trials, with measured soil temperature, moisture and inorganic N to mechanistically interpret flux changes.

Unknown net effect on carbon sequestration and subsoil SOC dynamics

Because a large fraction of global SOC is located in subsoil, altering horizon architecture could either expose formerly protected subsoil C to faster turnover or lead to stabilisation in a new context. Reviews of deep SOC responses to environmental change indicate complex controls on subsoil decomposition (59, 60). There are no meta-analyses or long-term measurements directly addressing whether CVR increases or decreases whole-profile SOC stocks or changes the mean residence time of SOC pools.

Recommended action: measure whole-profile SOC (0–1 m) with fractionation (particulate vs. mineral-associated C) and radiocarbon where possible to detect changes in SOC turnover following CVR.

Lack of mechanistic studies on mineral release, micronutrient availability and contaminant mobilisation

Chintala Venkata Reddy repositions mineral fractions and may increase the short-term availability of micronutrients (or mobilise bound contaminants). Mechanistic work on subsoil chemical responses to warming and moisture shows that soil chemical context controls decomposition and mineral release (60). However, direct measurements of mineral weathering rates, micronutrient solubility and potential mobilisation of heavy metals or salts following horizon mixing are largely absent for CVR.

Recommended action: conduct paired soil solution sampling (suction lysimeters), sequential extractions for bioavailable metals and short-term incubation experiments to quantify mineral dissolution and nutrient pulses after soil transfer.

No region-wise suitability mapping or decision-support tools

Adoption is likely to be highly site-specific (soil order, depth to restrictive layers, contaminant history, climate). Acceptance and experimental results for subsoil interventions vary strongly across regions (61). Yet there is no published, spatially explicit suitability map or risk matrix that synthesises edaphic, climatic and socio-economic criteria to guide where CVR is likely to be beneficial rather than harmful.

Recommended action: Develop a GIS-based suitability framework combining soil maps (texture, pH, salinity, parent material), land use history and risk layers (contaminant hotspots) and validate it with field trials.

Operational, social and lifecycle knowledge gaps (labour, mechanisation, energy and emissions)

Although often presented as a low-cost approach, the energy, labour and mechanisation requirements for scaling CVR are poorly quantified. Systematic reviews on mechanisation and subsoil amelioration note large variation in equipment needs and socio-economic constraints (62, 63). There is no published life cycle assessment comparing CVR to alternative soil restoration measures (e.g., compost, biochar, reduced tillage) in terms of emissions, cost or labour.

Recommended action: Include techno-economic analyses and cradle-to-farm LCA in research projects so that policymakers and farmers can compare CVR against other restoration options.

Future research directions

Despite growing interest in soil swapping methods, several structured research pathways are required to transform the technique from a practitioner-led innovation into a scientifically validated regenerative soil management practice. The following research directions are proposed, drawing on gaps identified in the soil restoration literature and aligning with global soil science frameworks (64).

Controlled experiments in research stations

Well-designed, replicated field experiments are essential to quantify treatment effects with statistical rigour. Research stations offer controlled conditions to monitor soil physical, chemical and biological changes following soil swapping interventions. Long-term trials are crucial to determine whether the improvements observed in farmers' fields translate into reproducible outcomes under scientific conditions. Similar long-duration experiments in soil restoration have proven essential for validating farmer-innovated practices (65, 66).

Key outcomes to evaluate nutrient turnover, aggregate stability, soil compaction relief, water movement across horizons.

Soil profile characterisation before and after swapping

A significant future priority is the thorough evaluation of soil profiles, encompassing morphological, physico-chemical and mineralogical alterations induced by the interchange of topsoil and subsurface layers. To track structural renewal, standardised soil pedon descriptions, bulk density profiles, clay mineralogy (X-ray diffraction) and hydraulic conductivity metrics should be recorded. Research on profile reconstruction following deep tillage and subsurface amendments (67, 68) underscores the significance of horizon-wise monitoring. Recommended tools include soil coring, WRB/USDA pedon classification, digital penetrometers and X-ray diffraction.

Microbiome sequencing and functional metagenomics

Soil swapping may bring dormant microbial communities from deeper layers into contact with oxygen, nutrients and root exudates. Next-generation sequencing (NGS) methods (16S, ITS, metagenomics, meta-transcriptomics) ought to be utilised to delineate alterations in microbial functional groups, enzyme activity and nutrient-cycling pathways. A better knowledge of how microbes change over time will help determine whether the technology accelerates the activation of helpful microbes or breaks up existing ecological networks (69, 70).

Focus areas: concentration on nutrient-solubilisers, carbon-use efficiency, stress-tolerant microbial guilds and enzyme stoichiometry.

Crop-specific optimisation and system integration

Different crops respond differently to changes in soil structure, aeration and mineral supply. Future studies should examine crop-specific responses to soil swapping, particularly for cereals, legumes and deep-rooted species. Optimising the depth, timing and scale of soil movement for each cropping system will improve agronomic reliability. Crop system-specific optimisation frameworks have been effective for other regenerative inputs such as biochar and conservation tillage (71, 72).

Possible directions: nutrient-use efficiency, root architecture adjustments, crop water use, interactions with nano-fertilisers.

Economic analysis and farm-scale decision models

Future work should incorporate cost-benefit assessments, labour and machinery costs, energy requirements, yield volatility and risk modelling. Bio-economic models can help determine farm-scale feasibility and adoption potential. Previous analyses of regenerative technologies have shown that economic viability significantly influences farmer uptake (73, 74).

Metrics to include: return on investment (ROI), payback period, labour-energy ratios, machinery amortisation.

Integration with digital soil mapping and geospatial tools

Digital soil mapping (DSM), GIS and remote sensing can support region-specific recommendations by predicting where soil swapping is most beneficial or risky. Integrating pedotransfer functions, terrain attributes, soil texture maps and moisture indices can help develop suitability maps. Applications of DSM in land restoration demonstrate the power of geospatial modelling for precision interventions (75, 76).

Outputs expected: suitability zonation, risk maps for cracking clay soils, depth-to-hardpan predictions, decision-support tools.

Long-term field validation

The majority of studies are short-term. Sustainability and resilience can only be tested using long-term experiments. Past research demonstrates that soil restoration and microbial dynamics vary over time (77).

Biochemical and microbial evidence of the soil

Existing studies are more focused on physico-chemical characteristics, whereas little attention has been given to biological indicators. Microbial diversity and soil enzymes play a vital role in nutrient cycling and ecosystem stability. The use of more sophisticated techniques such as metagenomics must be incorporated (78).

Multi-location validation trials

Agro-climatic regions exhibit different soil responses. Research has shown that there is substantial site-specific variability and that multi-location trials are required to ensure broader applicability (79, 80).

Environmental implications

There is a lack of studies on environmental implications. Soil restoration practices affect GHG emissions, carbon sequestration and contaminant dynamics (81). Potential risks, including contaminant transfer, microbial disturbance, etc., should be considered.

Conclusion

The CVR soil swapping technique is a farmer-led innovation designed to rejuvenate degraded soils by redistributing nutrient-rich subsoil to the surface and reactivating dormant microbial communities. Evidence from farmer observations and preliminary studies indicates improvements in soil structure, water infiltration and nutrient cycling, particularly in dryland agro-ecosystems. These outcomes suggest that the approach can enhance crop performance, reduce dependence on synthetic inputs and contribute to ecological resilience. While promising, the technique requires systematic validation through controlled, multi-location experiments and long-term trials to establish its agronomic effectiveness and ecological safety. With appropriate scientific assessment, economic viability studies and region-specific guidelines, the CVR soil swapping method has the potential to play a significant role in soil restoration, sustainable land management and the advancement of regenerative agriculture.

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Authors' contributions

LRS was responsible for the conceptualisation of the study, supervised the research work, prepared the original draft and contributed to the review and editing of the manuscript. BSSSN conducted the literature review and data curation. MMR was involved in data curation and investigation. KGR contributed to methodology development and validation of the study. AK performed visualisation and formal analysis. SS assisted with validation and resource management, while MRN contributed resources and investigation. VRN contributed to manuscript writing, review and editing. PG was involved in investigation and data curation. GKR contributed to the original draft writing. YPKR provided technical support and software assistance. JSB carried out proofreading and contributed to manuscript review and editing. SKY performed formal analysis and data curation. MMB supervised the work and managed project administration. GP contributed to software support and visualisation. KVR assisted

with editing and data analysis. RT revised the manuscript, while DAR contributed to data interpretation and manuscript revision. SC was responsible for validation and provided final approval of the manuscript. All authors read and approved the final manuscript.

Compliance with ethical standards

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References

- Lal R. Restoring soil quality to mitigate soil degradation. *Sustainability*. 2015;7(5):5875–95. <https://doi.org/10.3390/su7055875>
- Montanarella L, Pennock DJ, McKenzie NJ, Badraoui M, Chude V, Baptista I, et al. World's soils and their state. *Eur J Soil Sci*. 2016;67(1):5–11. <https://doi.org/10.1111/ejss.12345>
- Food and Agriculture Organization. State of the world's land and water resources for food and agriculture: systems at breaking point. Rome: FAO; 2020.
- Bhattacharyya R, Ghosh BN, Mishra PK. Soil degradation in India: status, challenges and strategies. *Curr Sci*. 2015;109(7):1205–19. <https://doi.org/10.3390/su7043528>
- Blagodatskaya E, Kuzyakov Y. Active microorganisms in soil: critical review of estimation criteria and approaches. *Soil Biol Biochem*. 2013;67:192–211. <https://doi.org/10.1016/j.soilbio.2013.08.024>
- Fenner N, Freeman C. Soil microbial responses to oxygen availability in managed ecosystems. *Glob Change Biol*. 2020;26(4):2201–14. <https://doi.org/10.1111/gcb.14987>
- Rumpel C, Kögel-Knabner I. Deep soil organic matter and subsoil processes. *Plant Soil*. 2011;338:143–58. <https://doi.org/10.1007/s11104-010-0391-5>
- Cornelis JT, Delvaux B, Cardinal D, André L. Silica release and availability during soil formation. *Geoderma*. 2011;163:120–31. <https://doi.org/10.1016/j.geoderma.2011.04.002>
- Huang M, Keller C. Weathering of Fe- and Mg-rich minerals under oxygenated conditions. *Chem Geol*. 2016;447:97–108. <https://doi.org/10.1016/j.chemgeo.2016.05.005>
- Uroz S, Calvaruso C, Turpault MP, Frey Klett P. Mineral weathering microbial communities. *Appl Environ Microbiol*. 2009;75(3):768–77.
- Hakansson I, Lipiec J. A review of the usefulness of relative bulk density values in studies of soil structure and compaction. *Soil Tillage Res*. 2000;53:71–85. [https://doi.org/10.1016/S0167-1987\(99\)00095-1](https://doi.org/10.1016/S0167-1987(99)00095-1)
- Logsdon SD, Karlen DL. Bulk density as a soil quality indicator during conversion to no-tillage. *Soil Tillage Res*. 2004;78:143–9. <https://doi.org/10.1016/j.still.2004.02.003>
- Blanco-Canqui H, Lal R. Principles of soil conservation and management. Dordrecht: Springer; 2008. <https://doi.org/10.1007/978-1-4020-8709-7>
- Brady NC, Weil RR. The nature and properties of soils. 15th ed. Upper Saddle River (NJ): Pearson; 2017.
- Rengasamy P. Soil processes affecting crop production in salt-affected soils. *Funct Plant Biol*. 2010;37:613–20. <https://doi.org/10.1071/FP09249>
- Lal R. Soil organic matter and global climate change. *Soil Sci*. 2016;181(3):113–22. <https://doi.org/10.1097/SS.0000000000000151>
- Busscher WJ, Bauer PJ. Soil strength, management and crop response in southeastern coastal plain soils. *Soil Tillage Res*. 2003;74:121–9. [https://doi.org/10.1016/S0167-1987\(03\)00162-8](https://doi.org/10.1016/S0167-1987(03)00162-8)
- Lal R, Shukla M. Principles of soil physics. New York: Marcel Dekker; 2004. <https://doi.org/10.4324/9780203021231>
- Mäder P, Fließbach A, Dubois D, Gunst L, Fried P, Niggli U. Soil fertility and biodiversity in organic farming. *Science*. 2002;296(5573):1694–7. <https://doi.org/10.1126/science.1071148>
- Schjonning P, Lamandé M, Munkholm LJ, Lyngvig HS, Nielsen JA. Soil precompression stress, penetration resistance and crop yields in relation to differently-trafficked, temperate-region sandy loam soils. *Soil Tillage Res*. 2016;163:298–308. <https://doi.org/10.1016/j.still.2016.06.014>
- Wani SP, Rockström J, Oweis T. Rainfed agriculture: unlocking the potential. Wallingford: CAB; 2016.
- Liu QY, Xu CT, Han SW, Li XX, Kan ZR, Zhao X, et al. Strategic tillage achieves lower carbon footprints with higher carbon accumulation and grain yield in a wheat-maize cropping system. *Sci Total Environ*. 2021;786:149220. <https://doi.org/10.1016/j.scitotenv.2021.149220>
- West JR, Whitman T. Disturbance by soil mixing decreases microbial richness and supports homogenizing community assembly processes. *FEMS Microbiol Ecol*. 2022;98(9):fiac089. <https://doi.org/10.1093/femsec/fiac089>
- Blanco-Canqui H, Ruis SJ. No-tillage and soil physical environment. *Geoderma*. 2018;326:164–200. <https://doi.org/10.1016/j.geoderma.2018.03.011>
- Akinci I. Effect of soil compaction on root growth and nutrient uptake of crops: a review. *J Agron*. 2004;3(3):163–8.
- Kuzyakov Y, Blagodatskaya E. Microbial hotspots and hot moments in soil: concept & review. *Soil Biol Biochem*. 2015;83:184–99. <https://doi.org/10.1016/j.soilbio.2015.01.025>
- Samaddar A, Raza Q, Ahmad M, Singh A. Soil mixing-induced changes in microbiome function and plant growth. *Appl Soil Ecol*. 2021;168:104117.
- Fierer N. Embracing the unknown: disentangling the complexities of the soil microbiome. *Nat Rev Microbiol*. 2017;15:579–90. <https://doi.org/10.1038/nrmicro.2017.87>
- Schneider N. Subsoil loosening and deep soil modification improve drought resilience. *Agric Water Manag*. 2017;191:67–78. <https://doi.org/10.1016/j.agwat.2017.06.002>
- Rumpel C, Lehmann J. Soil organic matter in the Anthropocene. *Nat Geosci*. 2020;13:693–700.
- Lehmann J, Kleber M. The contentious nature of soil organic matter. *Nature*. 2015;528:60–8. <https://doi.org/10.1038/nature16069>
- Lal R. Soil organic matter and sustainable agriculture. *J Soil Water Conserv*. 2020;75:27A–35A. <https://doi.org/10.2489/jswc.75.2.27A>
- Dexter AR. Soil physical quality: Part I. Theory, effects of soil texture, density and organic matter and effects on root growth. *Geoderma*. 2004;120:201–14. <https://doi.org/10.1016/j.geoderma.2003.09.004>
- Kennedy AC, Smith KL. Soil microbial diversity and agricultural sustainability. *Plant Soil*. 1995;170:75–86. <https://doi.org/10.1007/BF02183056>
- Doran JW, Zeiss MR. Soil health and sustainability: managing the biotic component of soil quality. *Appl Soil Ecol*. 2000;15:3–11. [https://doi.org/10.1016/S0929-1393\(00\)00067-6](https://doi.org/10.1016/S0929-1393(00)00067-6)
- Cassman KG, Dobermann A, Walters DT. Agroecosystems, nitrogen-use efficiency and nitrogen management. *Ambio*. 2002;31:132–40. <https://doi.org/10.1579/0044-7447-31.2.132>
- Reddy CV, Reddy VR. Subsoil biological reactivation and soil functional restoration. *J Soil Ecol*. 2019;45(3):221–30.
- Pii Y, Cesco S, Mimmo T. Exploring microbial activity in deep soil layers. *Plant Soil*. 2016;407:1–15.
- Reddy CV. A process to improve the nutrient contents of soil in cultivated lands. Patent WO/2006/001030. 2006.
- Smith P, Soussana JF, Angers D, Schipper LA, Chenu C, Rasse DP, et

- al. How soil carbon contributes to climate change mitigation. *Nat Commun.* 2020;11:1–8.
41. Topa DC, Căpsună S, Calistru AE, Ailincăi C. Sustainable practices for enhancing soil health and crop quality in modern agriculture: a review. *Agriculture.* 2025;15(9). <https://doi.org/10.3390/agriculture15090998>
 42. Berger I, Kamble A, Morton O, Raj V, Nair SR, Edwards DP, et al. India's agroecology programme 'Zero Budget Natural Farming' delivers biodiversity and economic benefits without lowering yields. *Nat Ecol Evol.* 2025;9:2057–68. <https://doi.org/10.1038/s41559-025-02849-7>
 43. Agegnehu G, Bass AM, Nelson PN, Bird MI. Benefits of biochar, compost and biochar–compost for soil quality, maize yield and greenhouse gas emissions in a tropical agricultural soil. *Sci Total Environ.* 2017;543:295–306. <https://doi.org/10.1016/j.scitotenv.2015.11.102>
 44. Jeffery S, Verheijen FG, van der Velde M, Bastos AC. A quantitative review of biochar effects on crop productivity. *Agric Ecosyst Environ.* 2011;144:175–87. <https://doi.org/10.1016/j.agee.2011.08.015>
 45. Bronick CJ, Lal R. Soil structure and management: a review. *Geoderma.* 2005;124:3–22. <https://doi.org/10.1016/j.geoderma.2004.03.005>
 46. Gill JS. Amelioration of dense sodic subsoil using organic amendments. *Field Crops Res.* 2008;107:54–60. <https://doi.org/10.1016/j.fcr.2008.02.014>
 47. Naylor D, DeGraaf S, Purdom E, Coleman-Derr D. Trends in microbial community composition by soil depth. *Front Microbiol.* 2022;13:860667. <https://doi.org/10.3390/microorganisms10030540>
 48. Hinzmann M, Ittner S, Kiresiwa Z, Gerdes H. An acceptance analysis of subsoil amelioration amongst agricultural actors in two regions in Germany. *Front Agron.* 2021;3:660593. <https://doi.org/10.3389/fagro.2021.660593>
 49. Proto M. Application of organic wastes to subsoil materials: long-term soil improvements. *Environ Technol Innov.* 2023;30:102959. <https://doi.org/10.1016/j.eti.2023.102959>
 50. Morales-Salmerón L, Fernández-Boy E, Madejón E, Domínguez MT. Soil legacy and organic amendment role in promoting the resistance of contaminated soils to drought. *Appl Soil Ecol.* 2024;195:105226. <https://doi.org/10.1016/j.apsoil.2023.105226>
 51. Ramesh V, Naidu MVS, Ramana K, Prasad PRK. Deep tillage effects on Vertisol structure and hydrology under rainfed conditions. *Soil Tillage Res.* 2019;194:104350.
 52. Ghosh H, Singh R, Maji AK. Physical risks of soil inversion in black cotton soils. *Geoderma.* 2010;156(1–2):57–64.
 53. Nyang'au D, Kihui J, Mwangi M, Kiptot E. Mechanization challenges in soil restoration technologies: implications for adoption and scaling. *Agric Syst.* 2023;213:103543.
 54. National Bureau of Soil Survey and Land Use Planning (NBSS & LUP). Soil map (1:1 million scale). Nagpur (IN): NBSS & LUP; 2004.
 55. Bai Z, Dent DL, Olsson L, Schaepman ME. Energy and labour requirements for soil horizon manipulation. *Land Degrad Dev.* 2018;29(9):3050–62.
 56. Reddy CV. A process to improve the nutrient contents of the top soil. Patent EP2272313A1. 2010.
 57. Hicks Pries CE, Ryals R, Zhu B, Min K, Cooper A, Goldsmith S, et al. The deep soil organic carbon response to global change. *Annu Rev Ecol Syst.* 2023;54(1):375–401. <https://doi.org/10.1146/annurev-ecolsys-102320-085332>
 58. Basheer S, Wang X, Farooque AA, Nawaz RA, Pang T, Neokye EO. A review of greenhouse gas emissions from agricultural soil. *Sustainability.* 2024;16(11):4789. <https://doi.org/10.3390/su16114789>
 59. Dexter AR, Richard G, Arrouays D, Czyż EA, Jolivet C, Duval O. Complexed organic matter controls soil physical properties. *Geoderma.* 2008;144(3–4):620–7. <https://doi.org/10.1016/j.geoderma.2008.01.022>
 60. Possinger AR, Weiglein TL, Bowman MM, Gallo AC, Hatten JA, Heckman KA, et al. Climate effects on subsoil carbon loss mediated by soil chemistry. *Environ Sci Technol.* 2021;55(23):16224–35. <https://doi.org/10.1021/acs.est.1c04909>
 61. Jansson JK, Hofmockel KS. Soil microbiomes and climate change. *Nat Rev Microbiol.* 2020;18(1):35–46. <https://doi.org/10.1038/s41579-019-0265-7>
 62. Jha S, Kaechele H, Sieber S. Factors influencing the adoption of water conservation technologies by smallholder farmer households in Tanzania. *Water.* 2019;11(12):2640. <https://doi.org/10.3390/w11122640>
 63. McBratney AB, Mendonça Santos ML, Minasny B. Digital soil mapping: a brief history. *Geoderma.* 2014;264:301–11. <https://doi.org/10.1016/j.geoderma.2015.07.017>
 64. Minasny B, Hartemink AE. Predicting soil properties in the tropics. *Earth-Sci Rev.* 2011;106(1–2):52–62. <https://doi.org/10.1016/j.earscirev.2011.01.005>
 65. Pittelkow CM, Liang X, Linquist BA, Van Groenigen KJ, Lee J, Lundy ME, et al. Productivity limits and potentials of the principles of conservation agriculture. *Nature.* 2015;517(7534):365–8. <https://doi.org/10.1038/nature13809>
 66. Pretty J, Benton TG, Bharucha ZP, Dicks LV, Flora CB, Godfray HCJ, et al. Global assessment of agricultural system redesign. *Nat Sustain.* 2018;1:441–6. <https://doi.org/10.1038/s41893-018-0114-0>
 67. Srinivasarao C, Venkateswarlu B, Lal R, Kundu S. Enhancing soil resilience in rainfed systems. *Curr Sci.* 2013;105:1071–9.
 68. Tittonell P, Giller KE. When yield gaps are poverty traps. *Field Crops Res.* 2013;143:76–90. <https://doi.org/10.1016/j.fcr.2012.10.007>
 69. Yang P, Dong W, Heinen M, Qin W, Oenema O. Soil compaction prevention, amelioration and alleviation measures are effective in mechanized and smallholder agriculture: a meta-analysis. *Land.* 2022;11(5):645. <https://doi.org/10.3390/land11050645>
 70. Cook SM, Khan ZR, Pickett JA. The use of push–pull strategies in integrated pest management. *Annu Rev Entomol.* 2013;52:375–400. <https://doi.org/10.1146/annurev.ento.52.110405.091407>
 71. Glenn DM, Puterka GJ, Vanderzwet T, Byers RE, Feldhake C. Hydrophobic particle films: a new paradigm for suppression of arthropod pests and plant diseases. *J Econ Entomol.* 2010;92:759–71. <https://doi.org/10.1093/jee/92.4.759>
 72. Mullens BA, Gerry AC, Lysyk TJ. Dust-based management of biting flies on livestock. *J Med Entomol.* 2000;37:475–82.
 73. Moyer JE, Crossley MS, Showler AT. Mineral-based deterrents in insect pest management: mechanisms and field performance. *Crop Prot.* 2018;110:1–9.
 74. Showler AT. Effects of water deficit stress, shade, weed competition and kaolin particle film on selected foliar free amino acid accumulations in cotton, *Gossypium hirsutum* (L.). *J Chem Ecol.* 2002;28(3):631–51. <https://doi.org/10.1023/A:1014556515489>
 75. Luo Z, Wang E, Sun OJ. Soil carbon change and its responses to agricultural practices: a meta-analysis. *Glob Change Biol.* 2018;24:2410–21.
 76. Karami A, Homae M, Afyuni M, Ruhipour H, Basirat S. Organic resource management: impacts on soil aggregate stability and carbon sequestration. *Geoderma.* 2016;282:1–9.
 77. Burns RG, DeForest JL, Marxsen J, Sinsabaugh RL, Stromberger ME, Wallenstein MD, et al. Soil enzymes in a changing environment: current knowledge and future directions. *Soil Biol Biochem.* 2013;58:216–34. <https://doi.org/10.1016/j.soilbio.2012.11.009>
 78. Delgado-Baquerizo M, Maestre FT, Reich PB, Jeffries TC, Gaitan JJ, Encinar D, et al. Microbial diversity drives multifunctionality in terrestrial ecosystems. *Nat Commun.* 2016;7:10541. <https://doi.org/10.1038/ncomms10541>
 79. Bünemann EK, Bongiorno G, Bai Z, Creamer RE, Deyn GD, de Goede R, et al. Soil quality – a critical review. *Soil Biol Biochem.* 2018;120:105–25. <https://doi.org/10.1016/j.soilbio.2018.01.030>

80. Paustian K, Lehmann J, Ogle S, Reay D, Robertson GP, Smith P. Climate-smart soils. *nature*. 2016;532:49–57. <https://doi.org/10.1038/nature17174>
81. Powlson DS, Whitmore AP, Goulding KWT. Soil carbon sequestration to mitigate climate change. *Eur J Soil Sci*. 2011;62:42–55. <https://doi.org/10.1111/j.1365-2389.2010.01342.x>

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