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Review

A comprehensive review on grapes (*Vitis* spp.) cultivation and its crop management

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Abstract
Grapes (*Vitis vinifera*) are extensively grown in tropical and sub-tropical climate for its wine as well as direct consumption as table grapes or raisin. Grape production substantially contributes to the economy of smallholder farmers of developing countries. Despite the relevance of grape production in the international market and the potential for boosting rural economy, the automation in grape production is very low. Mechanization in grapevine cultivation is an indispensable factor for timely operations and cost-savings. Therefore, the technological interventions for grapes production as well as its management in vineyards have been reviewed in the paper. Vineyards are undergoing a gradual transformation into a mechanized way with the advent of newer and ready to adopt technologies like planting, pruning, weeding, spraying, fertilizer application, irrigation and harvesting. However, selective in nature, some operations are still carried out manually like pruning, weeding, and harvesting in developing countries. Although complete mechanization is possible for each production and cultivation process tedious and labor-consuming practices must be prioritized for mechanization and automation. This review systematically summarizes the existing technologies and explores the future prospects for researchers to automate grapevine production and crop management technology for grapevine cultivation.

Article Highlights

- Grapes cultivation with emphasis on agronomic practices.
- Crop canopy management practices followed in vineyards.
- Advances in irrigation and fertigation system as well as weed management in vineyards.

Keywords Viticulture · Mechanization · Grapevine · Automation · Cultivation

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1 Introduction

Grape (*Vitis vinifera*) is a high valued and premium quality fruit crop which is substantially produced around the world mainly for wine production. However, due to its multifarious uses, this fruit has a large market for consumption as dried resins, table grapes, juice, vinegar, jelly, etc. [1–3]. Both tropical and temperate climatic regions are suitable for grapevine cultivation under a range of soil. China ranks first for grape production followed by Italy, USA, Spain, France, Türkiyeand India. About 77.8 mt of world grapes were produced from 7.4 mha area in 2018, of which 57% are for wine grape, 36% are table grape and 7% are dried grape [4, 5]. Grapevines are grown in 7.4 mha of the global area of which 50% of the world vineyard is represented by the five countries viz. Spain (13%), China (12%), France (11%), Italy (9%) and Turkey (6%).The grape market is expected to remain strong due to the high production growth in some areas such as Italy, USA, Spain, France, Turkey and India. Grape is a primarily crop of temperate region and has been widely adopted in tropical and subtropical conditions across the globe. Worldwide it is being grown mostly for wine, raisin, juice and fresh consumption over an area of 1.40 lakh hectares with production of 30.41 lakh tonnes [4].

Most of the operations involved in grapevine cultivation are mechanized (Fig. 1) but still growers follow manual methods in developing countries like India due to high machinery cost and selective operation viz. pruning and harvesting. The advent and recent advances in transplanting technologies suggest ample scope for working on automated mechanisms including robotics. Transplanting is a tedious, time-consuming and expensive operation that needs mechanization [6]. In viticulture, grape rootstocks are transplanted manually at specific intervals. Whereas, in the developed countries, complete operation is mechanized due to the involvement of the manufacturing industries, as irrigation is mostly done with pressurized irrigation system. Automation in plant protection technologies is essential and plays a crucial role in grape production. Intensive pesticide application is required in vineyards both for quantitative and qualitative production of grapes. Still to reduce the adverse effect of synthetic agrochemicals on human health and the environment there is a dire need for optimized use of agrochemicals using advanced tools and techniques for sustainable plant protection [7]. Several plant protection technologies for vineyard have been discussed in sub-section. Intercultural operations in vineyards are essential as the weed competition at initial 3–4 years considerably attributed to economic losses [8]. The degree of adverse effect of weeds differs throughout the life of the vineyard, hence control of weeds at critical stages of crop remains a priority. Weed competition can decrease survival, severely retard vine growth, and prolong the beginning of production stage. In grape vineyard, potential yield loss caused by weeds is reported to be 29.1–45.2% [9]. Moreover, they may interfere with harvesting, pruning, spraying equipment, and other cultural operations. Specifically, vineyards in temperate regions, weeds may lead to more severe frostbite in grapes because of reduced radiation from the soil.

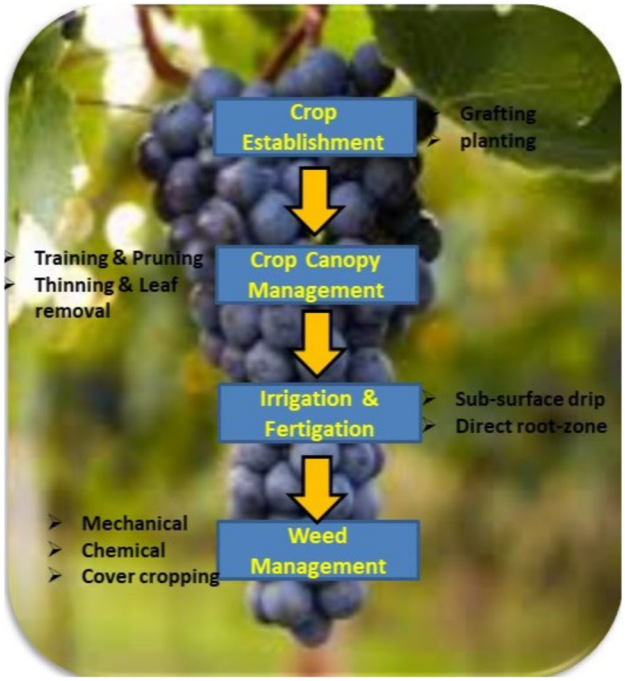

Fig. 1 Major operations in mechanized grapevine cultivation

Grasses are the most competitive weeds, poses severe challenge due to the perennial nature of grape orchards. In this context, herbicide application is seen as the easy, quick and inexpensive way for weed control; nevertheless, because of sustainable and environment friendly cultivation, practices adopting non-chemical measures are essential.

In recent years, grape production has increased chiefly for its wine production and hence, as a result whole cultivation practices have been mechanized starting from planting of rootstock to harvesting. Now it is time to supplement novel technologies using robotics and artificial intelligence (AI) with the traditional practices for higher productivity. Bochtis et al. [10] reported the use of traditional management methods with innovative sensing and driving technologies and improved information and communication technologies. Also, the automation using vision-based system is gaining popularity to increase productivity and efficiency in agriculture [11]. Hence, some of the advanced technology will be increasingly applied to the automation for grape production which has been summarized in Tables 1, 2, 3, 4 and 5. This review systematically summarizes the existing technologies and explores the future prospects for researchers to automate grapevine production.

1.1 Botanical description

Grape (*Vitis vinifera* L.) is a perennial climbing plant classified within the Vitaceae family. The family has been classified in detail by Planchon [55] who identified 10 genera and many subgenera of this family. Over time, the family has been expanded to 17 living and two fossil genera, including *Cissites* and *Paleovitis*. The two species belonging to genus *Vitis* are widely grown for their quality edible fruit in world viz. *V. vinifera* and *V. labrusca*. Formerly known as *Euvitis*, *Vitis* comprised two subgenera, *Vitis* and *Muscadinia*. However, *Muscadinia* is now recognized as a distinct genus, distinguished from *Vitis* by noticeable morphological variations in fruit and seed shape, the presence of a diaphragm, fruit retention at maturity, tendril morphology, and differences in chromosome numbers (i.e., *Muscadinia* with $2n = 40$; *Vitis* with $2n = 38$). *V. rutondifolia*, *V. munsoniana* and *V. popenoeii* are the three member species of the genus *Muscadinia* amongst them *V. rutondifolia* is only *Muscadinia* species being grown in America for their fruit but on very small scale [56]. *V. labrusca*, *V. raparia*, *V. rupestris*, *V. amurensis*, *V. beralndeiri*, *V. champanii*, etc. are important species falling under the genus *Vitis* having inherent resistance against different grapevine pathogens. Inter-fertility of all the species creates confusion on the number of species to be included in the genus *Vitis* [57].

1.2 Origin, domestication and worldwide dispersal

The grape (*Vitis vinifera* L.) is believed to have originated in the contiguous region around the Mediterranean basin and the Caspian Sea. From there, it spread to areas such as Asia Minor, Europe, and various countries where viticulture is prominent today [58]. *V. vinifera* is thought to have evolved from the wild type *V. sylvestris*, with *V. sylvestris* identified as its progenitor according to researchers [59–62].

The Vitaceae family, to which grape belongs, adapted to a broad range of climates, spanning temperate, subtropical, and tropical regions. The extensive genetic diversity of *V. vinifera* is evident in its cultivation, boasting over ten thousand cultivars worldwide. The domestication of grapes commenced in a geographical area between Iran and the Black Sea, expanding eastward. These eastern regions are now recognized as secondary domestication centers for grapes, as outlined by some researchers [63–69].

1.3 Climatic and soil requirement

Climatic parameters like temperature, relative humidity, frost occurrence and rainfall play an important part in commercial grapes cultivation. Generally, grapes thrive in a warm and arid climate. Essentially, it is a crop of temperate regions; however, successful grape cultivation has expanded to encompass sub-tropical and tropical areas globally. Regions characterized by high rainfall and humidity are unsuitable for the cultivation of grapes. Optimal grape cultivation occurs in areas with temperatures ranging from 15 to 40 °C and an annual rainfall between 500 and 600 mm. During the cropping period, clear weather for approximately 3–4 months is essential. Unfavourable conditions, such as low temperatures, high humidity, cloudy weather, and rain during flowering and berry formation phase, can be detrimental as they foster disease spread. Site and soil characteristics significantly contribute to global variations in vine production [70]. Although, grapes can adapt to diverse soils, they exhibit optimal growth in deep, medium-textured soils with good drainage and low salt content, such as sandy loams and loams. Salinity poses a major obstacle to grape development. Salinity causes main interference in the grape's development. It develops well in soils with pH of 6.5–8.0 [71, 72].

Table 1 Summary on crop canopy management in grape vineyards

Method/technology	Details/working principle	Advantages	Disadvantages	References
Mechanical pruning				
Tractor front mounted pruner	Modified M–O mechanical pruning unit use rotary cane positioner and cutter bars	Dormant cane pruning Time saving up to 54–70% Reduced cost by 56–80%	Difficult in Y or T type trellises due restricted movement of pruners along the row	[9, 12]
Trail type pruner. Pruning equipment was mounted on articulated frame, which is attached to a tractor	The cutting system consists of two sub-frames that carry cutting and shearing discs The vertical branches were cut by rotating discs and shearing discs, while the horizontal branches are by reciprocating bars	Grape pruner as an attachment for small tractors to mid-range vineyards The assembly can be easily disengaged, releasing the tractor for other tasks	–	[13]
Intelligent Autonomous Grapevine Pruner	Autonomous tractor with vision based system and pruning arm with cutter	Prunes bilateral cordon grapevines like manually Cuts on both sides of each grapevine	High cost Takes long time for operation	[14]
Automatic mechanical pruning head	Ultrasonic sensors were used for automatic opening of rotary cutters	For high cordon machine pruned trellis systems and vertical shoot positioned trellis systems	requires hand pruning as a follow-up for the final pruning cuts	[15]
Robotic pruner	Artificial intelligence (AI) system was used to identify the cutting location on canes to be pruned	Computer vision system and robot arm cuts the cane efficiently Less time required for pruning per vine	Long chain of inter-dependent components limits reliability High cost	[16]
Shoot thinning and leaf removal				
Mechanical pruning and leafing machine	Rotating rollers mounted on deleafing machine used to grip and pull the leaves	Reduce shoot density Helps to regulate yields Improve fruit zone microclimate Sunlight exposure and airflow as per the different growth stages	–	[17–20]

Table 2 Summary on irrigation and fertigation methods used in vineyards

Method/technology	Details/working principle	Advantage	Disadvantage	References
Surface irrigation	Irrigation water is supplied through the distribution pipes or channels by the force of gravity. Furrow as well as basin irrigation are used traditionally	Surface methods involve lower infrastructure Operational costs and easier to adopt	Encourage high evaporation and percolation losses Low water use efficiency and crop water productivity Labour intensive	[21]
Drip irrigation	Localized irrigation systems as the water is directly applied to the root zone by dripping the water near the crop roots emitter at very low rates (2–20 l/h)	Proper water and nutrient supply High productivity Less weeds and no requirement of heavy earth wok for field levelling	High initial investment Clogging problem Operation and maintenance requires skilled person	[22–24]
Sub-surface drip irrigation	Low pressure and low volume micro-irrigation system that uses buried drip tube/tapes and provides water directly to root zone of plants	Increased yield Negligible evapo-transpiration losses Lessor no weeds and high water productivity	High cost Difficult laying and retrieval process Smaller and localize wetting patterns may reduce crop root development	[25–27]
Deficit irrigation	Irrigation amounts equal or close to the crop water needs is supplied at the most drought sensitive growth stage. While, irrigation amount and frequency is drastically reduced for the rest of the growing period	Increased water productivity Improved harvest quality Reduced fertilizer losses and fertilizer input	Exact knowledge of water stress and crop response is required Drought sensitivity need to be accessed Increase soil salinity problem Reduction in yield	[28–32]
Regulated deficit irrigation (RDI)	It is a new irrigation management strategy, in which the plants are exposed to some degree of water stress for a predefined stage of growth season, aiming to achieve control on reproductive and vegetative growth and development, to improve water use efficiency	Controls excess water consumption Reducesinput costs and greatly influence the quality of berries	Heat stress to the plants Slow vegetative growth Reduction in yield	[33–36]
Partial root-zone drying (PRD)	A fixed fraction of the crop water needs is applied all throughout the irrigation season. Irrigation is applied daily or 2–4 times per week. Grower irrigate only half part of root system while simultaneously other part of the root system is kept dry for efficient plant water use	Enhanced water use efficiency Berry size and improved fruit quality Management tool for semi-arid and arid region Better control of vegetative vigour	Costly adapted irrigation system Drying of the roots at dry side Reduction in yield	[21, 37–39]
Fertigation	Fertigation is the application of dissolved/liquid fertilizers through a pressurized irrigation system. Drip irrigation is the most commonly used as fertigation system in vineyards, but fertigation can also be performed with micro-sprinklers	Uniform fertilizer application Flexibility with time Automation can be done Reduced fertilizer amount and cost Less labour requirement	Sensitive to clogging Require frequent maintenance Corrosion in the pipes Ca and Mg fertilizers precipitate in the pipeline	[40, 41]

Table 3 Available water content, root zone depth and allowable soil moisture depletion for different soil type

Soil texture class	Available water (mm/m)	Root zone depth (m)	Allowable depletion	
			Percentage (%)	Amount (mm)
Sandy	4.64	1.35	50	35.56
Loam	11.61	1.05	50	66.04
Clay	19.35	1.05	50	111.75

Table 4 Fertigation schedule for table purpose grapes [42]

Growth stage (days after pruning)	N (kg/ha)	P_2O_5 (kg/ha)	K_2O (kg/ha)
Back pruning			
Pre-bud differentiation (1–30 days)	80	–	–
Bud differentiation (30–60 days)	–	213	–
Post-bud differentiation (60–120 days)	–	–	80
Forward pruning			
Pre-bloom (30–60 days)	80	–	–
Bloom set and shatter (30–60 days)	–	106.6	–
Berry growth up to *Veraison* (30–60 days)	80	–	80
Veraison to harvest (30–60 days)	–	–	80
After harvest (Rest period)	26.6	35.5	26.6
Total	266.6	355.2	266.6

2 Grape cultivation

2.1 Land preparation

Land preparation for vineyard establishment is the primary as well as crucial operation. It is done with tractor operated plough to control the weeds like Bermuda grass (*Cynodon dactylon*) and nut grass (*Cyperus rotundus*) and leveled with leveler. Trench opening and filling are carried out before planting of grape rootstocks in the field which are done to loosen soil for good aeration. The trenching can be done with tractor drawn trencher. In India, this operation should be done during December–January months. The size of the trench like depth and width should be 750 × 750 mm and 61–76 m long with a spacing of 2.4–3.0 m as per requirement [72]. The trenching is done to invert the soil and it is kept open for 10–15 days before filling. Farmyard manure and a mixture of single super phosphate are added while filling the trench. The trench should always be made in North–South direction so as to plant the grapes on Y-system of training, so that plant can get equal amount of sunlight on both side and also prevent from sunburn during heat [72].

2.2 Nursery raising

Before planting, the grape rootstock cuttings are raised in the nursery. Generally, the nursery bed should be 1.5 m in length and 0.8 m in width. The rootstock cuttings are taken from the mother plant during September–October months and thus cuttings will be getting 3–4 months' time for root development before planting in February–March [72]. The rooted plants having 4–5 mature buds are transplanted in the polybags for root development and transported to other locations [72]. The polybags should be large enough for nutrient supply and good root development of cuttings in the bags.

2.3 Vineyard establishment

The planting of the grape rootstocks is done during the February–March months due to the rise in temperature, which is required for good root growth. The grapevines are generally trained in trellises i.e., Y or T-type trellis, bower, kniffin, head and slanting trellis. The trellises are made in the north–south direction. Whereas, the bower system prefers in the

Table 5 Summary on weed management technologies in vineyards

Method/technology	Details/working principle	Advantages	Drawbacks	References
Mechanical weed control method	Offset type disc harrow/cultivator, blade weeder and finger weeder controls weed by soil cutting and inversion Mower cuts cover crops and weeds into small pieces and left over it as mulch, hence restricts the weed growth	Most effective, environmentally friendly as it alters soil conditions favorable to crop growth Effective weed control Covers ground quickly Can be used when soil moisture limits the use of other soil working machines Mulch suppresses weed growth and enhances the soil fertility status	High operational cost Soil erosion due to excess soil manipulation Possibility of regrowth of some of annual and perennial weeds after cutting	[43]
	Combination of mechanical cutting element and spraying attachment for herbicides application	Site-specific application results in saving up to 80% of chemicals	–	[44]
	Swing arm controlled mechanical weeder	Effective for intra-row weeding in orchard	Inter row weeding not possible	[45]
	Robotic tiller weeder	For intra-row weeding only in vineyards Self-steering capabilities (based on the laser scanner) Trunk detection (based on electro mechanical and sonar sensor)	Not for inter row weeding Low working capacity (i.e. 0.57 km h^{-1})	[43]
	Under-row tiller with axial hoeing head	Lower in operational cost and energy requirement	Not for inter row weeding	[45]
	Free-active spin-harrow	For inter-row and within row cultivation	–	[46]
	Brush weeders	Flexible in operation More efficient because of its ability to work close to crop row	Weeding efficiency is low	[47, 48]
	Wonder Weeder-ground-driven under-tree cultivator	Operated at relatively high speed and this can cover a lot of ground quickly	Less effective against heavy sod and may not be used to move or level soil under trees	[95]
Thermal method	Gas burners are provided to deliver gas flame for weeding in the field	Faster rate Greater efficacy of weed removal	Higher material and machine cost Damage to crop if not handled carefully	[43, 50, 51]
	Steam or steam jet at high pressure is used for weeding	Good control of leafy weeds Faster rate No damage to main crop	Higher material and machine cost	[50, 52]
Cover cropping	Applying mulch	Checks soil erosion Improves soil structure and fertility status and limits the weed growth Increase in crop yield Better choice from environmental point of view	More costly as compared to hoeing and chemical spraying	[53, 54]

Table 5 (continued)

Method/technology	Details/working principle	Advantages	Drawbacks	References
Chemical weed control	Herbicide applicator/boom sprayer	Relatively inexpensive Quickly done More effective method	Proper selection of herbicides critical Require good application techniques Not environment friendly Not work with all weeds	[44]
	Sensor coupled spray applicators uses optical sensor to determine weed location	Reduction in herbicides use More efficient and effective	Costly compared to conventional sprayer Technical skill is required	[54]

east–west direction for better spray convenience. Tractor drawn digger or post-hole digger is used for making holes at equal intervals for the trellises. The selection of a trellis depends on the variety of grapevine, climatic conditions and level of mechanization needed.

2.4 Grafting

Grafting is a method where a rootstock of mother plant is attached to the scion of a healthy plant. It is generally done manually with the help of grafting knife during the September–October depending on ecological and cultivation conditions. The success of the grafting usually depends on the skill of the person. The climatic condition suitable for grafting is 30–35 °C temperature and around 80% relative humidity [72]. Generally, grafting can be done by two methods in situ grafting and grafting in nursery. The in situ grafting is done on the matured rootstock planted in the field for higher success rate. Whereas in case of grafting in nursery, the cuttings are planted in the poly bags and grafting has less success rate and also requires more attention as compared to in situ method [72]. Hence, in situ method was preferred over grafting in the nursery.

2.5 Planting of rootstock

Before erecting trellises, the rootstocks were planted in the field by digging a pit at an equal interval of 1.5 m and 2 m distance in light and heavy soils, respectively. The pit size is 300 × 300 × 300 mm. Generally, these pits are dug manually [72]. However, some hand-held or tractor operated diggers can be used for making holes and then they can be reshaped manually. The planting operation is done manually because no transplanter is available for transplanting grape rootstocks in the field. Vinomatos Ltd [73] developed a satellite-guided planting machine for vineyards which guaranteed accuracy and effectiveness in planting. The machine can plant up to 20,000 vines per day. It cuts a deep slot through the soil, places/inserts each vine at the exact distance from the previous, and finally firms the soil back around the vines.

Hence, the erection of trellises and transplanting of grape rootstock needs prime attention due to the non-availability of a fully automated transplanter for grapevines.

3 Grapevine canopy management

Crop canopy management (CCM) should be carried out in viticulture for sun and air exposure to leaves, maintaining quantity and quality of the crop, avoiding disease incidence and severity, and improving crop health, efficiency and sustainability. The CCM is also a labor intensive operation, if not done can reduce the production of quality grapes. Two major CCM practices are (1) training and pruning; and (2) shoot thinning and leaf removal (Table 1). Generally, pruning is done to maintain good vine structure and regulate cluster growth. Whereas, shoot thinning brings balance between in vegetative and fruiting by reducing shoot density in grapevines. RDO Equipment Co., US; FMR Group Ltd, New Zealand; V-Mech, California; Blueline Mfg. Company, Washington; etc. are the leading manufacturer of vineyard equipment in the world.

3.1 Training and pruning

Training and pruning are the most essential operations required for higher grape production by controlling the crop size in any vineyard. The grape shoots must be well trained in trellis or arbor for good growth. The grape yield is higher in a well-pruned grape plant. Pruning is essential for development of new shoot growth. Generally, the pruning operation is done manually with the help of hand-held pruning secateurs or cutters. However, some pruners attached to the tractor were also available to ease the operation.

Pruning is the most laborious viticulture practice before and after harvesting in the two-pruning and single crop system of grape production and in general as well. Many mechanical pruning machines have been available for decades and are used for pre-pruning by grapevine growers. However, the finishing is done manually. The hand pruning reduces the number of nodes left behind by mechanical pruning which may result in over-cropped vines. Depending on the degree of mechanization, the cost associated with pruning can be reduced by 56–80% [74]. Gatti et al. [12] reported that mechanical pruning could have a time-saving ranging from 54 to 70% compared to hand pruning. Also, a fully mechanized single high-wire Barbera trellis can be managed by 70 man-h/ha. Mechanical pruning becomes problematic when

the grapes are grown in Y or T type trellises due to restricted movement of pruners along the row. Also in India, farmers practice hand pruning, which involves skill operation, resulting in higher yield.

Santos and Moreira [13] developed a grape pruner as an attachment to a small tractor for application in small to mid-range vineyards for small business grape growers. An Intelligent Autonomous Grapevine Pruner was developed for grapevine which consisted of an autonomous tractor, vision-based system and a pruning arm with a cutter [14]. The developed pruner prunes bilateral cordon grapevines with the same quality as done manually. The pruning mechanism consists of two cutting arm which prunes each grapevine from the both sides ensuring efficient operation and quality of pruning. It moves 0.45 m then stops, cuts and moves again.

An automatic mechanical pruning head was developed for high cordon machine pruned trellis systems and vertical shoot positioned (VSP) trellis systems as an attachment to V-MECH tool carrier by Midwest Grower Supply Mfg. in 2016. The prototype was designed to perform all pruning operations in one pass, including final pruning using five ultrasonic sensors to automatically open rotary cutters. But, it also requires hand pruning as a follow-up for the final pruning cuts. Botterill et al. [16] developed a robot system for automatic pruning of grapevines using a computer vision system. An artificial intelligence (AI) system was used to identify the cutting location on canes to be pruned by developing a 3D vine model using a computer vision system and then a robot arm of 6 DOF to cut the cane. The result indicated that 8.4 canes were cut by the robot arm in each vine and the total time required to prune one vine was 2 min in the field. Morris et al. [75] reported that pruning methods had more effect on yield components than time of thinning. Also, less pruned vines had lower cluster weights, berry weights, and yield per node as compared with hand pruning at the harvesting stage.

3.2 Thinning and leaf removal

The most important seasonal CCM practice for grapevine is shoot thinning, if not done will result in congested canopy. This will enhance excessive disease incidence due to reduced airflow, high humidity and extended damp periods. The dense canopy will increase the drying time for tissues and will further limit the penetration of fungicide spray. Thinning of both shoot and fruit is the most time-sensitive practice essentially regulating crop yield. Generally, it is done manually but some mechanical leaf removal or shoot thinner are also available.

Mechanical shoot thinners may be used to reduce the shoot density of mechanically pruned vines, thereby helping to regulate yields, improve fruit zone micro-climate, and produce fruit of similar or better quality as hand-pruned vines. Leaf removal is generally carried on grapevines to allow sunlight exposure and airflow at different growth stages. Leaves removal by hands is a time-consuming, labour-intensive operation, and involves high cost. Due to labour shortage, the leaf removal was done with deleafing machines. These machines can operate efficiently where the grapevines are grown with trellises due to uniformity in fruit distribution along the cordon. Leaves are also removed from the grape plant by the leaf removers using rotating rollers. These rollers can grip and pull the leaves from the branches. Some trimmer cutter beams can be used with one to seven knives for leaf removal. RDO equipment [17] is one of the leading manufacturers of pruning and leafing machines.

Cantacuzene [18] reported that leaf removal from or below the cluster on the shoot to be avoided since those provide carbohydrates for the developing cluster. Also, it should not completely strip from the fruiting zone, to provide about 40–60% exposure to the clusters [19]. Bunea et al. [20] also reported that the application of a greater number of green works viz. shoots thinning, shoots tipping, removal of sylleptic shoots and partial defoliation, yields a better quality of grapes.

Pruning and thinning are the most time-consuming operation in viticulture. Although, many mechanical pruners are available, farmers still think hand pruning is the best as it is selectively done. Pruning also generates a huge amount of residue which can be used as fuel and energy generation by using proper residue management technology such as mulching and bailing.

4 Irrigation and fertigation

Changing climatic situations as well as injudicious management of water has led to moderate to severe shortage of irrigation water supply in the main grapevine growing zone of the world. Hence, this situation has shifted the attention of vine growers to adopt modern and judicious water management practices in grapevine production. In viticulture, regulating the amount of irrigation is one of the most important and challenging practices for achieving a proper balance between reproductive and vegetative growth. Type and frequency of irrigation depends on variety, location (climate),

soil–water capacity, vigor, and trellis design. However, irrigation management practices differ based on the end-use of berries. In the case of wine production, small and thick skin berries are preferred whereas, for table grapes long and thin skin berries are preferred. A little soil moisture depletion especially during bud breaking and the pre-veraison stage can cause delayed and uneven sprouting, leading to growth inhibition and an increase in the harvesting time. However, excess soil moisture leads to excess vine growth, resulting in an improper ratio of reproductive and vegetative development [76]. For quality berry production, a high canopy growth at the beginning stage and slow growth of grapevine during the veraison and berry ripening stage is desirable for reducing competition between canopy growth and berries development, which results in faster sugar accumulation within the berries [21]. The brief details of different irrigation and fertigation techniques are given in Table 2.

4.1 Irrigation methods

Traditionally grapevines are irrigated with surface methods of irrigation i.e., furrow and basin irrigation (Fig. 2). Surface methods involve lower infrastructure, and operational costs and easier to adopt. However, these methods encourage high evaporation and percolation losses, which lower water use efficiency and crop water productivity. Lot of efforts have been given to develop other water-saving irrigation techniques such as PRD (partial root-zone drying), DI (Deficit Irrigation) and RDI (regulated deficit irrigation) on different temporal scales to improve water productivity and fruit quality of various horticultural crops [25, 28–30, 77, 78]. In the viticulture, deficit irrigation (DI), regulated deficit irrigation (RDI) and partial root-zone drying irrigation (PRDI) are the most popular irrigation strategies to facilitate vineyard irrigation. But over the years, various water saving techniques viz. alternate furrow irrigation (AFI), DI and root zone drying irrigation (RZDI) have been adopted over conventional irrigation to improve water productivity and harvest quality. But still in-depth study is required to develop surface irrigation water saving techniques for different agro-climatic zones, soil conditions, cultivation practices and farm sizes. The amount of water loss in irrigation can potentially be reduced by adopting modern irrigation methods. These systems are water and energy efficient, which will increase yields, input use efficiency, and economic returns of woody perennial crops [26].

Likewise, subsurface drip irrigation (SDI) and direct root-zone irrigation have also emerged as promising water-saving irrigation strategies in a number of horticultural crops [79]. The effect of subsurface irrigation system has been evaluated for qualitative and reproductive parameters in grapevine cultivation worldwide [26, 27]. The subsurface irrigation method results in increased yield without any significant reduction in berries quality as compared to other traditional methods [25]. However, some disadvantages like smaller and localize wetting patterns may reduce crop root development in SDI system, which need to be resolved [79]. Therefore, various modifications have been incorporated in these

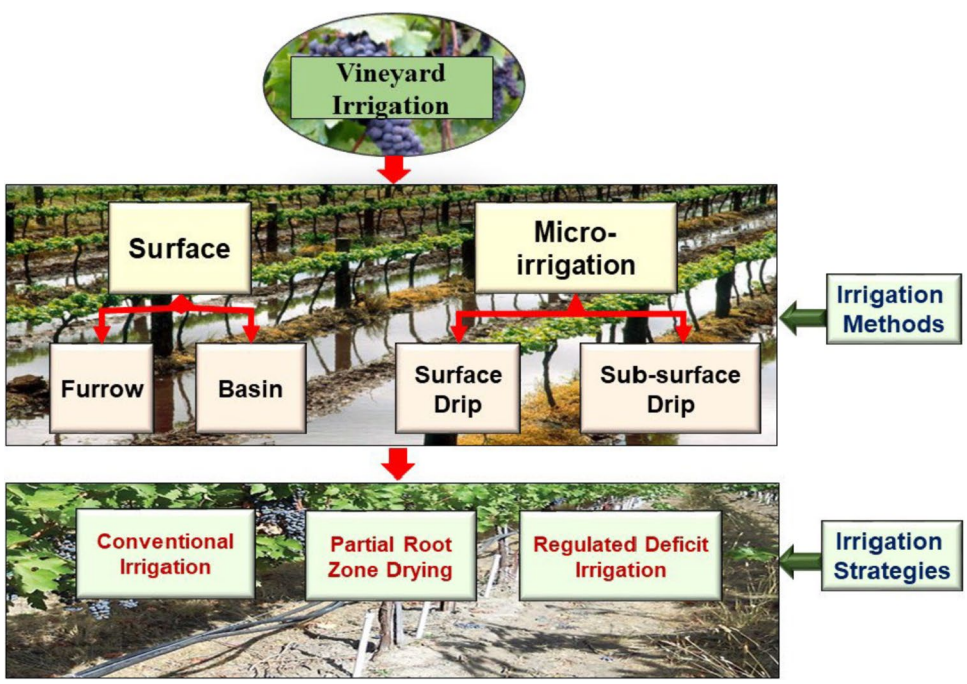

Fig. 2 Irrigation management practices for vineyards

irrigation systems' design and installation process, by changing the emitter type, buried depth, distance between emitters and planting geometry.

Some advancements involve innovative designs, such as incorporating sensors, visual techniques, remote sensing techniques and computer programming to make systems friendlier and smart [27]. Various information systems (e.g. 300viti; AgTech: Vineyard; PureSense; Ranch system; e-vineyard, AgriSense), mobile applications, decision support systems as well as weather based advisories, make the irrigation scheduling easier and accurate for the famers. Automation in grapevine irrigation facilitates users with uniform water application, save inputs and associated costs, and above all saves time of application.

4.2 Irrigation scheduling

While considering irrigation water management in the vineyard, it is necessary to establish a proper irrigation schedule based on the soil type, crop growth stage, weather, soil moisture available water source, and its quality parameters. Judicious irrigation scheduling in vineyards controls vine growth, prevents water stress, manages berry size, and maintains fruit quality and sugar accumulation in the berry by influencing pH, or soluble solids. Decision on irrigation scheduling requires a carefully considering of all factors that affect plant water status and irrigation management strategies to achieve desired berry quality and productivity. The supplied irrigation water must match the evaporative demand of grapevine. The water stress develops when the amount of irrigation water is less than the evaporative demand of the plant. However, plant stress may develop when there is restricted root growth system, unbalanced shoot and root ratio, and/or salty irrigation water. Wample and Smithyman [42] provided approximate data on available water content, root zone depth, and allowable soil moisture depletions for different soil textures (Table 3). The amount of water depletion is obtained by multiplying available water × root zone depth × percentage allowable depletion. To avoid stress, irrigation must occur after the vineyard uses this amount of water.

Grapevines do not immediately exhibit symptoms of water stress, but will slowly develop effects on shoot or berry development as a result of cumulative stress. Sharma [40] has summarized the impact of water stress at different physiological stages of the grapevine. Depending upon the physiological stages of grapevine, water stress widely affects vine growth, development and fruit quality. The main physiological stages of vine growth are bud break, flowering, fruit set, *Veraison*, harvest and post-harvest. The amount of irrigation water application differs at each growth stage. Based on the fraction of annual water use, a high amount of water (approximately 60%) is required during the fruit set to *veraison* stage. However, irrigation strategies viz., RDI, PRD and DI can be adopted for desirable fruit quality and water saving during this stage. *Veraison* to harvest period uses about 20% of annual water use. During the initial phase of this period, water stress may affect the sugar accumulation and flavouring components of the berry. But before reaching the harvesting stage, irrigation volume can be reduced to a significant level without compromising berry quality and quantity. Flowering to berry set period uses about 15% of annual water use. This stage is the most sensitive to water stress and an assured water supply should be provided by vine grower. While bud break to flowering and post-harvest period uses less than 10% of annual water use. Irrigations during these stages are likely to benefit vine growth by providing sufficient moisture for leaf functions and root development.

Vines must be irrigated just after pruning and fertilizer application and during berry development. Irrigation must be provided at 5–7 days of intervals. Irrigation is stopped at least 8–10 days before harvesting to improve the harvest quality and is resumed after pruning. Over irrigation during 45–50 days after summer pruning may inhibit the flower initiation by promoting excess vegetative growth and during blooming to the berry development stage, excess irrigation water can increase the problem of downy mildew.

Hence, drip irrigation is the most promising irrigation technique for vineyard growers with regulated deficit management strategies so as to ensure high-quality berries without compromising the yield.

4.3 Fertigation

Grapevines require a high amount of fertilizer input for proper growth and nutrition, since the fertilizer use efficiency of vines is very low, which is only 5–10% for N, 5–7% for P, and 6–12% for K fertilizers [40]. Therefore, heavy doses of fertilizers are applied throughout the growing season and fertilizer cost alone account for about 50% of the total grape production cost. The main macro-nutrients for plant growth viz., nitrogen, potassium, phosphorus, and magnesium as well as other micro-nutrients such as copper, zinc, boron, iron, calcium, and manganese can be applied through fertigation. Along with fertilizers, other liquid chemicals such as herbicides, fungicides, insecticides,

chlorine, and acid can be supplied through a fertigation system. The time to apply fertilizers is decided based on visual observations and interpretations of vine tissue analyses during the growth period. The fertilization schedule for table purpose grapes is given in Table 4.

An accurate amount of fertilizer may be applied through manual interventions or using automatic control system based on pre-defined fertigation schedules. This leads to better distribution and higher uniformity of fertilizer application. The optimum pH value of fertilizer solution should be in the range of 6.5–8.0. A variety of injection pumps (diaphragm, piston, roller and gear pumps), venturi injector system or simple fertigation tanks are used for fertilizer application to the plants [41].

5 Weed management

Weed management refers to an overall approach of minimizing weed infestation to prevent yield and quality losses of fruit crops due to improved crop growing conditions. Effective weed management strategy involves implementing one or more strategy in combination with the cultural method, physical method, chemical method and biological method. Specifically, for vineyards in temperate regions, weeds may lead to more severe frost bite in grapes because of reduced radiation from the soil. Some of the mechanized weed management techniques are summarized in Table 5.

5.1 Mechanical weed control

The choice of mechanical methods employed in weed control is governed by various factors such as crop, soil type, coverage area, the severity of weed infestation, operating cost, and labour requirement. Mechanical weed control may involve weeding the whole crop, or it may be limited to selective intra-row or inter-row weeding. Hand weeding may be combined with mechanical inter-row weeding to deal with weeds left in the crop row. For cultivation and weed control of intra-row space in vineyards, equipment like offset rotary hoe, offset type disc harrow/cultivator, blade weeder, finger weeder and brush weeders are considered more effective. Also, a mower is the equipment that cuts weeds and cover crops into small pieces, and leaves material on the soil surface as mulch, which suppresses or inhibits the growth of weeds.

Tamagnone et al. [44] developed a mechanical prototype coupled with a cutting element (to remove weeds within a row) and spraying attachment for herbicide application only at plant trunk and pole locations. Sehsah [53] developed a swing arm controlled mechanical weeder for effective intra-row weeding in orchard crop trees, which identified orchard trees and circumvented trunk location while weeding out remaining area. Manzone et al. [45] used an under-row tiller with an axial hoeing head assisted by the electro-mechanical sensor for weed control in a grape vineyard. They observed it lower operational cost and energy requirement and produced satisfactory results. Yezekyan and Olt [46] developed a tractor hydraulic powered free-active spin-harrow for inter-row and within row cultivation in vineyards specifically, for rocky soils. The prototype used a rubber bezel to bypass vines or any other obstacle during tillage between the plants in a row. The cutting elements returned to their original position after vine passes, performing tillage within the crop row.

A wide range of brush weeders are also being used in fruit orchards and grape vineyards due to their flexibility in operation. Vester and Rasmussen [47] compared the row brush hoe with a conventional hoe in horticultural crops and observed that the brush hoe was more efficient because it worked very close to the crop row. In another study, Kouwenhoven [48] reported that a brush weeder with rotating blades fixed ahead of brushes could control only half of the weed population even in loose soil. Tractor-mounted hydraulic rotary under-tree cultivators come with rotating tines hydraulically-powered could perform many orchard practices, including hilling up soil, removing berms in the tree middle, breaking up established sod, and general cultivation.

An autonomous robotic tiller weeder was developed for intra-row weeding capable of self-steering in vineyard rows (based on a laser scanner) and trunk detection (based on electro-mechanical and sonar sensors). The robotic weeder was provided with a rotary tiller unit powered by an electric motor for intra-row weeding. It was evaluated at a forward speed of 0.57 km h^{-1} and a working depth of 40 mm [80].

Some cost-effective technologies viz. tractor-mounted cultivators or mowers may be employed for weed control in vineyards. These cultivators may be operated at relatively high speeds (8.0–11.0 km h^{-1}) and can quickly cover a lot of ground. Mowing is more advantageous even when soil moisture limits the use of other soil working machinery; besides this, it relatively covers the ground quickly.

5.2 Chemical weed control

In vineyards, periodic applications of herbicide through combinations of pre-emergence and post-emergence herbicides are required to provide effective and economical control. Primarily, two types of herbicide applicators are available; an over-the-row frame type used to simultaneously spray both sides of the target row, or a boom that can be fitted to the front of a tractor to spray one side of two adjacent rows. Another type of sprayer is the controlled droplet applicator (CDA), which uses a spinning disc under a plastic dome that shields the vines from contact with the herbicide. This method was used to destroy weed seeds at pre-emergence or post-emergence stages of weeds, in combination with adequate preventive methods.

In flame weeding, LPG-fueled burners were used to control young weeds in mature vineyards. Flame weeding was one of the most popular weed control methods in developed countries in the 70's due to its faster rate but, its adoption is less due to higher cost. Hydrogen can also be used as a replacement for fossil fuels [50]. Hatcher and Melander [43] reported good results using pre-emergence flaming followed by post-emergence brush weeding or hoeing. As an alternative to conventional fossil fuel, Pergher et al. [51] developed and tested biomass fueled flaming prototype in vineyard. The results indicated that the weed removal efficacy of the developed flamer prototype was higher than conventional tillage implements between and around the vines.

Alternatively, steam or steam jet at high pressure can be used for weed control during crop growth. Kurfess and Kleisinger [52] used hot water (85–95 °C) for weed control in orchards. A similar study was reported on the use of steam jets to kill emerged weeds [50]. To improve the effect of thermal treatment, some work is initiated in the UK on weeders that use hot foam, which remains for a longer time on weeds and has more heat effects.

5.3 Combined mechanical and chemical weed control

Tamagnone et al. [44] developed a combined mechanical and chemical weed control system for the application of herbicides to plant collar, which saved chemical use significantly. The sensor-coupled spray applicator uses an optical sensor to determine weed location and sub-sequentially sends a control signal to the micro-controller unit for activation of nozzles for spray and resulting in a significant reduction in herbicide use [53]. In comparative evaluation, Manzone et al. [45] observed that boom spraying performed at par with mulching operations and able to maintain weed coverage below 30%. However, chemical spraying is not promoted from the environmental point of view if other effective, sustainable and environmentally friendly options are available.

Several manufacturers are involved in developing high quality, advanced, and efficient machines for herbicides application in vineyards, realizing the importance and commercial value of the grape crop. Two models of sprayer i.e. Under-vine vineyard sprayer and the Weedseeker selective spot spray system developed by Pastro™, Australia are claimed to be more efficient, and effective and reduce the drift significantly. The selective spot spray system uses optical sensors to detect weeds and spray only at identified locations, cutting input costs and saving chemical costs up to 80%.

5.4 Weed control by cover cropping

Cover crops are grown in the vineyards to check soil erosion, improve soil structure and fertility status, and limit weed growth. The cultivation of cover crops viz. annual medic and ryegrass in the under-vine zone has resulted in increased vine yields, soil quality, and financial returns [81]. Green manure cover crops can be planted in autumn and incorporated using a rotary hoe or disc harrows in spring, enhancing the soil's organic carbon [82]. Mechanical methods such as mowing, rolling crimping and undercutting use different commercially available machines to shred off the cover crop and leave it over the soil surface, serving as good quality mulch. Manzone et al. [45] reported that the use of a mulching machine resulted in similar weeding efficiency as with a sprayer. Still, the cost of operation was higher as compared to hoeing and chemical spraying. Nevertheless, it is a better choice from environmental concern point of view.

Since weed control throughout the season of grapes consumes a considerable share of production cost, mechanical weeders ranging from basic hand tools to sophisticated tractor-driven or self-propelled robotic systems have been developed. Chemical weed control is the most effective and economical one, but selecting suitable herbicides which are not harmful to the crop is a critical task, to avoid adverse soil or environmental impact due to indiscriminate use of chemicals.

6 Viticulture under climate change

Viticulture is highly sensitive to environmental conditions, making it especially vulnerable to the impacts of climate change. Increasing global temperatures, changes in rainfall patterns, and a rise in extreme weather events like heatwaves and droughts present major challenges to grape production and quality. Over the past 20 years, climate change has become a growing concern in viticulture and enology research. For instance, in 2011, 23 French research labs collaborated on the LACCAVE project to investigate how climate change affects viticulture and explore potential adaptation methods [83]. Today, a wealth of research examines how climate change influences various aspects of viticulture, such as vine physiology, phenology, grape composition, and wine quality [84–86]. In many wine-growing regions, grape harvest dates have advanced by 2–3 weeks over the last four decades. Adaptive strategies like altering plant material and cultivation techniques to delay ripening have been effective in managing rising temperatures up to a certain point [87]. One of the most immediate consequences of climate change on viticulture is water scarcity, which can negatively affect both grape quality and yield. Effective water management is essential, with precision irrigation techniques, such as drip irrigation, offering a potential solution by maximizing water-use efficiency and reducing stress on the vines [88]. Adjusting canopy management by using shade nets can also help protect vines from excessive heat and mitigate its negative impact on grape quality. Additionally, organic soil management practices, including cover cropping and composting, can improve soil health and boost vine resilience to climate variability [89]. Breeding programs play a vital role in developing grapevine varieties that can better withstand the changing climate. These programs should focus on traits such as drought tolerance, heat resilience, and disease resistance. As water availability becomes more unpredictable, breeding drought-resistant grape varieties will be crucial for maintaining vineyard productivity in water-limited regions. Similarly, heat-tolerant grape varieties will be necessary as higher temperatures become more common during the growing season [90]. Furthermore, climate change is fostering the spread of pests and diseases, making it essential to breed grapevines with improved resistance to common pathogens, thereby reducing the need for costly and environmentally harmful chemical treatments [91]. The integration of artificial intelligence (AI) in viticulture presents innovative solutions for optimizing vineyard management in response to climate change. Precision viticulture, powered by AI-driven algorithms, can analyze large datasets from drones, satellites, and sensors to monitor vine health, soil moisture, and disease outbreaks [92]. This data-driven approach enables growers to make informed decisions about irrigation, pest control, and harvesting, reducing input costs and minimizing waste. Moreover, AI-based predictive analytics can forecast weather patterns and help vineyard managers prepare for extreme events, while also identifying the optimal harvest time based on environmental factors and grape maturity [93]. AI-powered robotics for tasks like pruning and harvesting also enhance labor efficiency, reduce costs, and minimize human error [94]. A comprehensive review of AI and big data applications in viticulture can be found in Newlands et al. [95]. In addition, AI-driven automation can help optimize resource use, including energy, water, and labor, lowering operational costs. Sustainable farming practices, such as reducing chemical inputs and emphasizing organic or agroecological methods, can yield long-term financial benefits by improving soil health and reducing pest pressures [90].

7 Challenges and future prospects

The mechanization in vineyard i.e. crop establishment and crop canopy management is low and inefficient compared to other operations. Since most of the grape rootstocks are planted in the trellises and trellises systems hinder the mechanization. Suitable planting technology which will make mechanical intervention possible for inter-cultural operations as well as harvesting is highly needed. Mechanical pruners are also not so efficient. Hence, final pruning and thinning are done manually in grapevines. Therefore, the future research should be directed towards automatic planting as well as pruning and thinning technologies. For table grape production, modification in trellis design is very essential to mechanize intercultural operations viz., shoot thinning, berry thinning, and leaf and bunch removal to reduce hand labour inputs. To perform these operations selectively, robotic systems assisted with machine vision capabilities would be more efficient. Currently, most of the irrigation in vineyards is done with drip irrigation with regulated deficit management strategies. However, complete automation of vineyard irrigation system is still a far vision for small and marginal farms. Extensive research and development activity on irrigation automation needs to be carried out that should be sustainable under changing climatic situations.

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