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Editorial

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Coal Seam Methane Abatement and Utilization Techniques with Availability and Feasibility Criteria

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ABSTRACT

Methane found in coal seams is about 17% of total methane emissions by human activities and 8% of world's greenhouse gases emissions. Mine methane can be generated through different streams of coal mines like degasification of underground coal mines, ventilation of air in coal seams, post mining processes and surface mining. Methane from ventilation air is the most abandoned form obtained from coal seams but its utilization as an energy source is very difficult due to high flow rate and low concentration of methane in vented air. This discussion not only includes VAM's mitigation but also its utilization techniques which have been developed mostly based on oxidation and underdeveloped with their technical feasibilities and operational parameters.

1. Introduction

Methane released from coal seems is about 17% of the emission from human activity resource and 8% of total emissions of greenhouse gases [1]. Coal mine methane is actually refers the methane release before, during and after operational mining. There are three streams of methane emitting from gassy mines: (1) ventilation air methane (2) coal bed methane and (3) abandoned mine methane. Table 1 shows the percentage of emissions of gassy mine methane. Methane released during coal mining could be diluted through ventilation fans. Methane exhausted after dilution into atmosphere called ventilation air methane is about 64% of the total release from coal seams [2].

Ventilation air methane mitigation and utilization as an energy source are not an easy task because of its dilution and variation in concentration and flow rate. Low concentration of methane in VAM is a major problem and it can only be resolved by enriching the methane's concentration through some techniques but still there is no effective technology available to increase methane concentration so all the work is being done on focusing on low content ventilation air methane oxidation. According to combustion kinetic mechanism there are two types of oxidation, thermal and catalytic. There are two basic classifications of utilization technologies of ventilation air methane one for the supplementary uses and the other for the principle uses. Supplementary usage technologies are gas turbines, coal-fired power stations and internal combustion engines where combustion processes used ventilation air as a substituent for ambient air. While in the principle usage technologies VAM is used as a primary fuel. This technology includes CANMET catalytic flow reversal reactors (CFRR), MEGTEC thermal flow reversal reactors (TFRR), CSIRO lean burn catalytic turbine, EDL recuperative gas turbine and CSIRO catalytic combustor (CMR) that could be in combination with adsorption chiller and coal drying or heating or cooling. CFRR and TFRR can mostly provide only mitigation of methane by combustion to minimize greenhouse impact without extracting energy for power generation while turbine technologies are effective for both mitigation and extraction of methane. 1% and 1.6% methane concentration is required respectively which could be obtained by the combination of VAM and gassy mine drainage gas. Through successful installation of a concentrator, the concentration of methane could be increased up to 30% and it would make a breakthrough for the utilization techniques development [3].

Table 1: Gassy mine methane emission

Gassy mine streams	Percentage of Methane
Ventilation Air	0.1-1%
Pre Mining drainage gas	60-95%
Post Mining drainage gas	30-95%

This review categorized not only the currently developed coal mine mitigation and utilization techniques but also discusses the underdeveloped techniques with their feasibility for implementation. In Figure 1 there is a detailed classification of methane mitigation and utilization techniques according to their principles, mechanism and application.

2. Mitigation of Drainage Gas

It is possible to mitigate methane from coal mining. We can capture methane from coal mines for different applications

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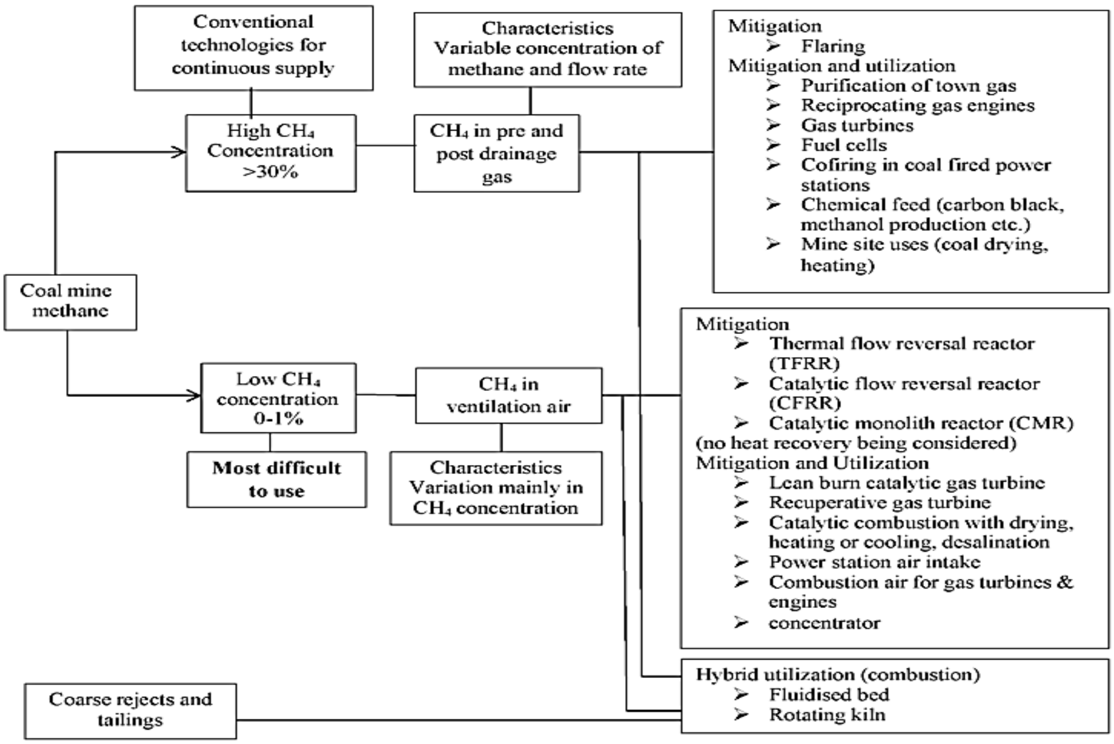

Figure 1: Classification of methane mitigation and utilization techniques with their feasibilities

Table 2: Technology classification of drainage gas

Technology	Mechanism	Principle	Application Status
Purification • Purification for towm gas	Separation	Gas purification process	Demonstrated in full scale units providing pipeline gas
Power generation/cogeneration • Reciprocating gas engine • Conventional gas turbine • Co-firing in power stations • Fuel cell power generation	Combustion Combustion Combustion Electrochemical reaction	Combustion in engine combustion Combustion in conventional gas turbine/engine Combustion inside boilers Electrochemical process	Utilization-demonstrated Utilization-demonstrated Utilization-demonstrated Utilization-being proposed as a concept
Chemical feedstocks • Chemical feedstocks: methanol and carbon black	synthetic	synthetic processes	Utilization-being tested in a pilot scale unit

Table 3: Main and distinguishing features of purification technologies

Technology	**Solvent adsorption**	**Pressure swing adsorption**	**Cryogenic separation**	**Membrane separation**
Sorbent	Liquid	Solid	n/a	n/a
Phase change	No	No	Yes	No
First stage Deoxygenation	Yes	No	Yes	
Methane recovery	96-98%	Up to 95%	98%	
Technical issues for application	Unsuitable for nitrogen removal	Small to medium size		Scaling up problem

and during these applications CH_4 is converted into carbon dioxide and due to this the impact of greenhouse reduces to 20 times [4].The following are some of the abatement options of drainage methane [5-9]:

a. Installation of vapour recovery units and flare systems.
b. In production install flash tank separators.
c. Replace high bleed with low bleed pneumatic devices.
d. Installation of plunger lifts system.
e. For pipeline venting use portable compression evacuation.

f. Green completions.
g. Fuel gas retrofit for blow down valve.
h. Direct inspection and maintenance at compressor stations.

3. Utilization Options for Drainage Gas

Concentration of drained gas is more than 30% could be used in different areas of industries. Table 2 shows a technology classification for drainage gas. US EPA has been summarized some of the option for the utilization of coal mine methane for drainage during and after mining operations [10]. These include:

- Coal mine methane can be used in blast furnaces, brine water treatment, cogeneration power systems, fuel cells, greenhouses, methanol production and coal dryers.
- Usage for heating mine ventilation air.
- Usage of coal-firing coal mine methane in industrial boilers.
- Formation of synthetic fuels.
- Increasing concentration of medium quality coal mine gas.
- Usage in internal combustion engines placed at coal mines.

All these technical options can be classified in three categories according to their applications: purification for gas pipelines, power generation and chemical feed stocks.

3.1. Town gas pipeline purification

Coal mine composed of 30-90% methane which could be the most effective source of fuel but it is generally vented to the atmosphere after its drainage. In fact sometimes it has been flared in mine which results a valuable loss of energy [10, 11]. Solvent adsorption, membrane separation, cryogenic separation and pressure swing adsorption are the main processes used for gas pipelines purification [12, 13]. Table 3 illustrates main features and differences of this technique.

3.2. Electricity generation

Generating power from drainage gas is an important option because of its significant electricity load. Every equipment needs electricity to run for instance mining machines, coal production plants, ventilation fans, conveyor belts and desalination plants. In fact ventilation system is running 24 hours a day and it utilizes large amount of electricity [11]. Table 4 shows power generation technologies with their feasibilities.

3.3. Chemical feed stocks

Coal seam methane can be used alternatively in chemical processes for the preparation of chemicals and synthetic fuels. Carbon black and methanol production are the two basic applications in this field [14, 15]. Table 5 shows distinguishing factors of these two technologies.

4. Ventilation Air Methane Mitigation

Coal mine methane has to be recovered for the safety of working environment and its utilization in various applications. Methane from coal seams is mostly emitted as ventilation air methane which has a very low concentration of CH_4 due to large volume of air so its utilization became more difficult. To reduce the overall impact of methane gas towards greenhouse effect it is very important to increase its concentration before utilization. Still there is no effective technique to maximize the methane percentage in ventilation air but working on its development is under progress until then majority of work has been focused on the VAM's oxidation. Oxidation reduces greenhouse gases impact 20 times [16-18].

4.1. Oxidation of methane

In this process methane is converted into carbon dioxide through its combination with oxygen as well heat is released which in turn used as energy source. Oxidation of VAM could be thermal or catalytic. The overall combustion reaction is represented by the following equation however many free radical chain reactions are involved in its actual reaction mechanism [19]:

$$CH_4 + 2O_2 \rightarrow CO_2 + 2H_2O, \quad H = -802.7 \text{ KJ/mol}$$

Carbon monoxide (CO) and carbon dioxide (CO_2) are produced by the increasing or decreasing air to methane ratio which are given as:

$$CH_4 + 2O_2 \rightarrow CO_2 + 2H_2O$$

$$CH_4 + \tfrac{3}{2}O_2 \rightarrow CO + 2H_2O$$

Other parallel reactions are given as:

$$CH_4 + H_2O \rightarrow CO + 3H_2$$

$$2H_2 + O_2 \rightarrow 2H_2O$$

$$CO + H_2O \rightarrow CO_2 + H_2$$

Catalytic oxidation is a multi-step process which involves:

- Diffusion to the catalyst surface.
- Adsorption on to the catalyst.
- Reaction.
- Desorption of the product species from the catalyst surface.
- Diffusion back into the bulk.

Figure 2 shows a catalytic oxidation mechanism proposed by Oh et al. [20]. For complete oxidation at low temperature it is observed that Palladium and Platinum are the most active catalyst. Lee et al. [19] experimentally proved that Pd/Al_2O_3 by far the best catalyst followed by Pt/Al_2O_3.

5. Utilization Techniques of Ventilation Air Methane

VAM is used as supplementary (ancillary) fuel and principle fuel in different technologies [21, 22]. Table 6 shows mitigation and utilization techniques for principle and ancillary fuel usage.

Table 4: Distinguishing characteristics of mine methane fired power generation technologies

Technology	**Gas engines**	**Gas turbines**	**Fuel cells**	**Co-firing in power stations**
Mechanism	Combustion	Combustion	Electrochemical reaction	Combustion/rebuming
Operating Temperature	1800-2000ºC	1400-1650ºC	150-200ºC, 600-950ºC	1400-165s0ºC
Maximum CH_4 Requirement	40% (spark ignition), 5% (homogenous compression ignition)	30 % (conventional), 1% (catalytic turbine)	Pre-drainage gas and medium quality post drainage gas (> 50%)	Not determined
Potential issues			Still underdevelopment, high cost	Limited sites

Table 5: Comparison of production technologies of carbon black and methanol

Technology	**Methanol Production**	**Carbon black production**
Mechanism	Synthesis reaction	Gas reduction reaction
Operating Temperature	130-1000ºC	150-1400ºC
Minimum CH_4 requirement	89%	Pre-drainage gas and medium quality post drainage gas (> 50%)
Potential Issues	Process water required	Process water required

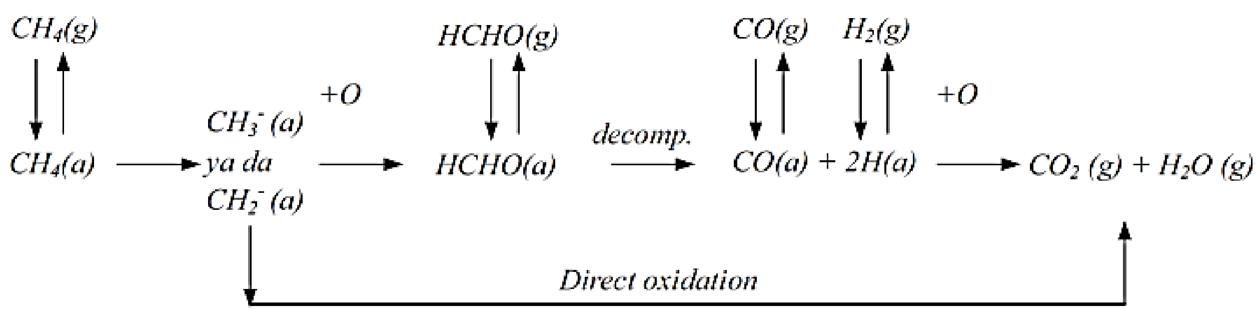

Figure 2: Catalytic oxidation mechanism for methane (a) adsorbed, (g) gas phase

Table 6: Ventilation air methane technology classification as supplementary fuel

Technology	**Oxidation mechanism**	**Principle**	**Application status**
Combustion air for conventional power station	Thermal	Combustion in of power station boiler furnace	Mitigation Utilization--demonstrated in a pilot scale unit. and being considered for a full scale demonstration
Combustion air for gas turbines	Thermal	Combustion in conventional gas turbine combustor	Mitigation Utilization--studied
Combustion air for gas engine	Thermal	Combustion in gas engine combustor	Mitigation Utilization--demonstrated
Hybrid waste coal/ methane combustion in a kiln	Thermal	Combustion inside a rotating combustion chamber	Mitigation Utilization--being preliminarily trailed in a pilot scale unit
Hybrid waste coal/ methane combustion in a fluidized bed	Thermal	Combustion inside a fluidized bed and freeboard	Mitigation Utilization--being proposed as a concept
Thermal flow reverse reactor (TFRR)	Thermal	Flow reverse reactor with regenerative bed	Mitigation: demonstrated Utilization--not demonstrated yet
Catalytic flow reverse reactor (CFRR)	Catalytic	Flow reverse reactor with regenerative bed	Mitigation: demonstrated Utilization--not demonstrated yet
Catalytic monolith combustor	Catalytic	Monolith reactor with a Recuperator	Mitigation: demonstrated Utilization--not demonstrated yet
Catalytic lean burn gas turbine	Catalytic	Gas turbine with a catalytic combustor and Recuperator	Mitigation: combustion demonstrated Utilization--being developed in a lab scale unit
Recuperative gas turbine	Thermal	Gas turbine with a recuperative combustor and Recuperator	Mitigation: combustion demonstrated Utilization--demonstrated in a pilot scale unit but needed further modification
Concentrator	N/A, adsorption	Multi stage fluidized/ moving bed using adsorbent, and a desorber	Mitigation and utilization: under development

5.1. Principle fuel technologies

In combustion processes ventilation air methane can be utilized as a primary fuel [23, 24]. However, methane concentration in ventilation air sometimes does not meet with the operational requirement for a primary fuel applications, specially where a high quality supplementary fuel is required to recover energy for power generation [17, 25].The following are the some applications of VAM as principle fuel.

5.1.1. TFRR (thermal flow-reversal reactor), CFRR (catalytic flow reversal reactor) and CMR (catalytic monolith reactor) Technologies

Principles of these three technologies are described in different places [23, 26, 27]. Both thermal and catalytic reactors work on flow reversal mechanism where Catalyst is the only difference between TFRR and CFRR [1]. TFRR oxidizes greater than 95% of CH_4 while CFRR oxidizes 90% of CH_4 in ventilation air methane in order to reduce greenhouse effect and valuable source of energy [28, 29]. Catalytic monolithic reactor implies a honeycomb type monolithic reactor. Because of its enormous benefits like high mass flows with very low pressure, high mechanical strength and high geometrical area, it is mostly used [30]. Some of the comparison features of these technologies are tabulated (Table 7). Figures 3, 4 and 5 are representing schematic diagram of TFRR, CFRR and CMR.

5.1.1.1. Concentration of methane

The low and variable concentration of methane in ventilation causes serious operational problems using TFFR and CFRR to generate power by recovering heat. A firm which manufactured TFRR, MEGTEC, has reported that thermal flow reversal reactors can show a sustain operation at 0.08% concentration of methane. However, another simulation results by S. Su., et al. indicated that if the concentration of methane is dropped down to 0.35% blow out would occur [31]. For a sustain operation of CFRR methane concentration should be above 0.1% [31]. Figure 6 shows the advantage of catalytic flow. An experimental result carried out by the work on catalytic combustion indicated that CMR will perform continuously if concentration of methane is not below 0.4% and a recuperate preheated the air up to 500ºC by using flue gas from the catalytic monolith reactor [31, 32].

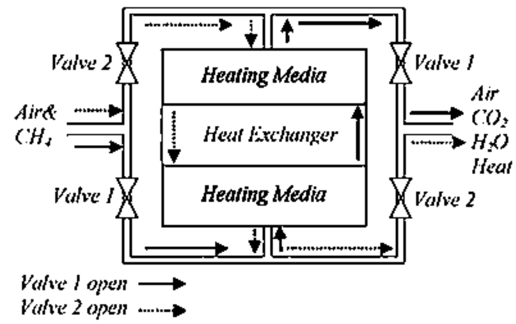

Figure 3: Schematic diagram of TFRR

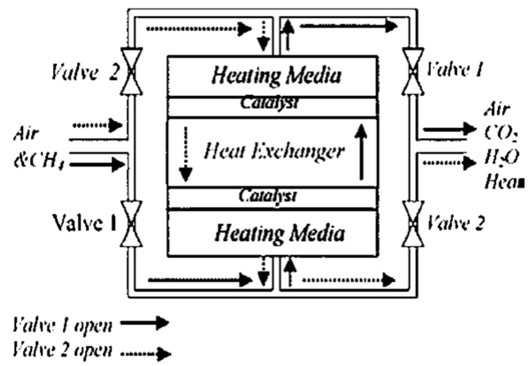

Figure 4: Schematic diagram of CFRR

Table 7: Distinguishing features of reactor technologies using VAM as primary fuel

Features	**Thermal flow reversal reactor**	**Catalytic flow reversal reactor**	**Catalytic monolith reactor**
Principle of operation	Flow reversal	Flow reversal	Monolith reactor
Catalyst	No	No	Yes
Auto ignition temperature	1000ºC	350-800ºC	500ºC
Cycle Period Length	Shorter	Longer	Continuously
Minimum methane Concentration	0.2%	0.08%	0.4%
Applicability	Methane mitigation	Methane mitigation	Methane mitigation
Variability of methane concentration	Variable	Variable	Variable
Plant ize	Huge	Lager	Compact
Operation	More Complicated	More Complicated	Simple
Lifetime	N/A	N/A	>8000h for catalyst
NO_x emission	N/A	Low	Low(< 1 ppm)
CO_x emission	Low	Low	Low(≈ 0 ppm)
Possibility of recovering heat to generate power	May need additional fuel to increase methane concentration and maintain it constant	May need additional fuel to increase methane concentration and maintain it constant	May need additional fuel to increase methane concentration and maintain it constant

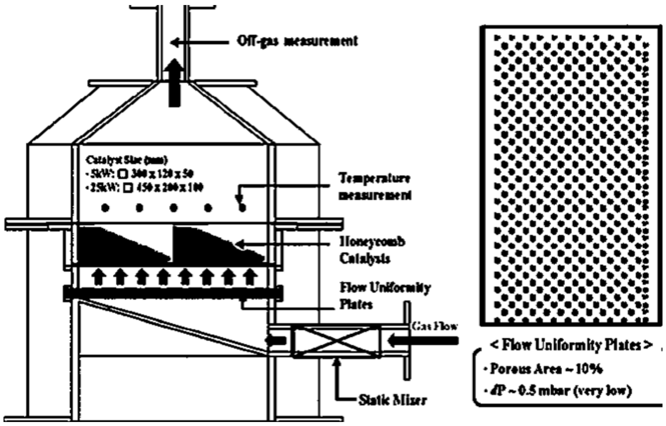

Figure 5: Schematic diagram of CMR

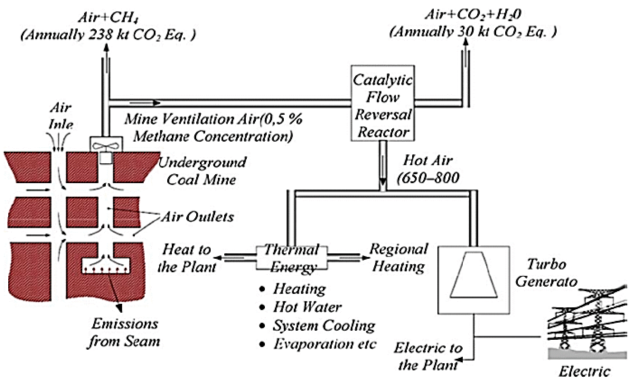

Figure 6: Advantages of catalytic flow

5.1.1.2. Recovery of heat

Heat extracted by combustion of methane for power generation highly depends on the constant methane concentration if it varies there is instability in the system and recovery of heat becomes difficult. It should only be possible if the concentration of methane above the minimum. This requires transference into the working fluid for example steam for a steam turbine and air for gas turbine. Some of the heat is needed to stabilize the temperature of the reactor and if the concentration of methane below its requirement most of the heat consumes in maintaining the temperature of the reactor. If the concentration of methane in ventilation air varies it is very difficult for normal heat exchangers to cope with the fluctuated temperature of the reactor. Experimental results carried out by Danell et al. [27] in the pilot thermal flow reactor unit have already been proven it. Therefore, an almost constant concentration of methane is required for recovery of heat for electricity generation which in turn requires addition of natural gas in feed air [33].

5.1.2. Lean burn gas turbines

In the modern world there are different lean burn gas turbines have been developed with a catalytic combustor which includes CSIRO lean burn catalytic gas turbine, Ingersoll Rand micro turbine and EDL's recuperative gas turbine. Most of the heat from the combustion process to pre heat the VAM used by recuperative gas turbines. Table 8 represents some important difference among lean burn gas turbines. If the concentration of methane in vent air not above 2% there must be an addition of CH_4 in the feed air so as to be used as a subsidiary fuel. Methane recovered from pre and post mining operations and low concentrated methane in ventilation air can also be used in these turbines [34]. An experimental result obtained from the recovered methane of two gassy coal mines of Australia which implemented 0.8% and 2% methane in gas turbines and found that 50% to 60% of the fuel for igniting 1% methane catalytic turbine while 30% to 60% of the fuel for igniting methane catalytic turbine is the ventilation air methane. It has also found that almost 100% ventilation air using 0.8% methane concentration for turbines and approximately 30% to 50% ventilation air used 2% methane concentration for turbines [35]. Figure 7 represents a schematic diagram of Lean burn gas turbines.

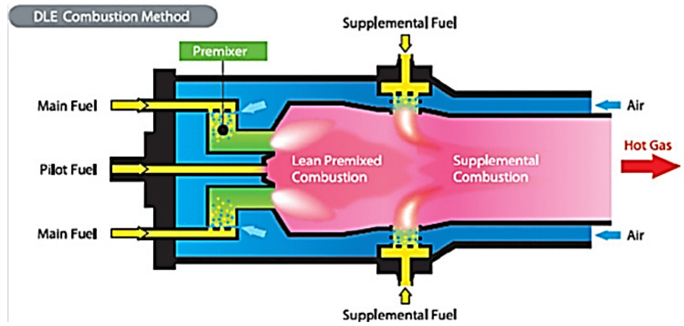

Figure 7: Illustration of Lean Burn Gas Turbine

5.1.3. Concentrators

In several industries volatile organic compounds are recovered through concentrators. They enrich the concentration of methane in vent air and meet the requirement of concentrators. Concentrators increase the concentration of methane in ventilation air from 0.8% to above 20%. As a result of enrichment if methane's concentration raised up to 30% then VAM could be used in conventional gas turbines for power generation [35].

5.2. Supplementary (ancillary) fuel technologies

The recovered VAM can be used as supplementary fuel to raise the combustion performance in the process of combustion. Basic utilization of VAM as ambient air are hybrid waste/coal methane combustion unit, gas turbines, pulverized coal-fired power stations and internal combustion engines. There is an uncertainty in the recovery of energy from these technologies because these units have safe connection to the mine shafts. But this mine site application and cannot be fully demonstrated and examined [3, 36, 37]. Table 9 illustrates comparison of supplementary usage of VAM technologies.

5.2.1. Hybrid waste/coal methane combustion units

Considering the mechanism of oxidation replacement of combustion air with ventilation air in hybrid waste/coal methane combustion in a fluidized bed and rotating kiln is same as the combustion of pulverized coal in boiler furnaces. However, the stabilization and organization principles of the combustion process are different [36].

5.2.1.1. Fluidized bed

Numbers of pilot scale units utilizing ventilation air methane as a subsidiary fuel in units of fluidized bed combustion

Table 8: Distinguishing characteristics of Lean Burn Gas turbine techniques

Feature	EDL recuperative turbine	CSIRO catalytic turbine	IR catalytic micro turbine
Principle of operation	Air heater inside combustion chamber	Monolith reactor	Monolith reactor
Catalyst	No	Yes	Yes
Auto ignition temperature	700-1000ºC	500ºC	N/A
Experience	Pilot Scale	Bench scale study on combustion	Conventional micro turbine development
Cycle Period Length	Continuously	Continuously	Continuously
Minimum methane Concentration	2.0%	0.08%	0.08%
Applicability	Methane mitigation and power generation and need additional fuel to increase methane concentration	Methane mitigation and power generation and need additional fuel to increase methane concentration	Methane mitigation and power generation and need additional fuel to increase methane concentration
Possibility of recovering heat to generate power	Feasible	Feasible	Feasible
Variability of methane concentration	Constant	Constant	Constant
Operation	Simple and stable	Simple and stable	Simple and stable
Lifetime	May be shorter due to high temperature combustion heat exchanger	>8000 h for catalyst, 20 years for turbine	N/A
NO_x emission	Higher	Low (< 3 ppm)	Low
CO_x emission	Low	Low (≈ 0 ppm)	Low

Table 9: Comparison of supplementary VAM usage technologies

Technology	Feature	Combustion temperature	Technical feasibility and engineering applicability	Potential issues
Pulverized coal fired power station	Pulverized coal fired furnace	1400-1650ºC	Tech: yes Engg: not demonstrated at a mine site	Limited sites Potential operational problems to existing boilers
Hybrid waste coal methane in a rotating kiln	Rotating kiln	1200-1550ºC	Tech: may be Engg: not demonstrated at a mine site	Self-sustaining combustion Minimum requirement for waste coal quality
Hybrid waste coal/ methane in a fluidized bed	Fluidized bed	890-950ºC	Tech: may be Engg: not demonstrated at a mine site	Minimum requirement for waste coal quality Proving test needed for CH_4 oxidation
Conventional gas turbines	Gas turbine	1400-1650ºC	Tech: may be Engg: not demonstrated at a mine site	Small percentage of turbine fuel A lot of CH_4 is emitted in by passing air for a single compressor machine. If two compressors are used there is increasing system complexity, and decreasing capacity of using ventilation air.
Internal combustion engines	Engine	1800-2000ºC	Tech: yes Engg: not demonstrated at a mine site	Small percentage of engine fuel using a small percentage of ventilation air

are preferred, even though there is no complete oxidation of methane occurs in these fluidized bed [38]. During the combustion process fluidized beds suspend solid fuels on upward blowing jets of air because of this there is a turbulent mixing of solids and gas. Bubbling of fluid gives more effective transference of heat and chemical reaction. All this process occur between the temperature of 800-950^{O}C. The flue gases from the fluidized bed come in contact with sulphur absorbing chemicals like limestone. Adsorbent capture these more than 90% of these sulphur pollutants inside the boiler. Circulating fluidized bed is much more effective in operational point of view because it could deal with high flow rate of air, moving bed material, recirculation of high volume of bed material and hot cyclone separators. So this technique is potentially more significant in terms of simplified feed design and extension in the contact between flue gas and adsorbent, tube erosion and improves the efficiency of combustion and adsorption of sulphur dioxide [39]. Figure 8 represents a fluidized bed combustion reactor.

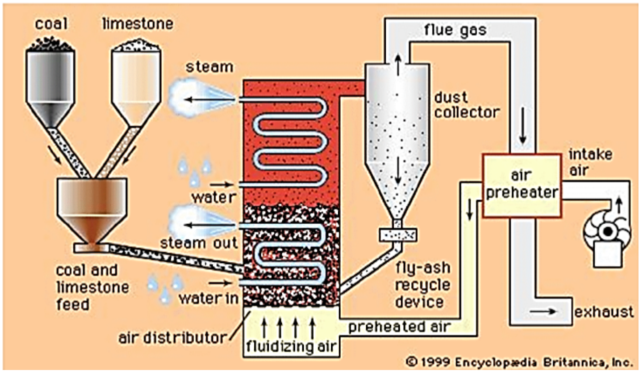

Figure 8: Diagram of Fluidized bed reactor

5.2.1.2. Rotating Kiln

In early 1990's, the combustion performance of waste coal has been examined by Cobb [40]. The test results concluded that it was very difficult to carry out a sustain combustion process even a sufficient amount of supplementary fuel were used. Rotary kiln is not well suited for the combustion of low grade hard coal because of its open structure which can be applicable for burning of bulky fuels and wastes. Figure 9 illustrates the working of a rotary kiln. CSIRO Exploration and Mining not only wants to mitigate methane but also recover waste energy for generating electricity. They are quite promising about the efficient operational results from the combustion of waste coal in combination with drainage gas and vent air both inside the rotary kiln. But still there number of parameters is left for investigation to obtain feasible physical conditions in kiln for sustain combustion of waste coal and it seems to be difficult.

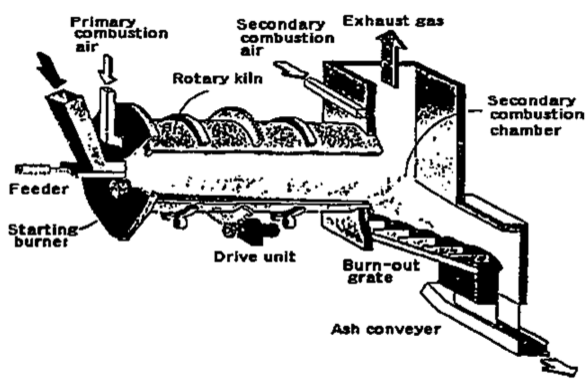

Figure 9: Diagram of Rotary Kiln

5.2.2. Conventional gas turbines

In this technique a small percentage of methane from ventilation air combines with the required fuel of turbine. This ventilation air not only diluted the combustion process but also cools down the turbine and because of it a sufficient fraction of methane will pass through the turbine without any combustion. To avoid this incomplete combustion a complex turbine system that not only require compressed from other source but also needed compressed ventilation air [34, 41]. If VAM is used with solar turbines then the concentration of methane should lower than 0.5% in order to maintain the unit system cool. If the concentration increases there will be more combustion and temperature of the inside of the rotor will raised up to a dangerous level [23]. Figure 10 shows a conventional gas turbine.

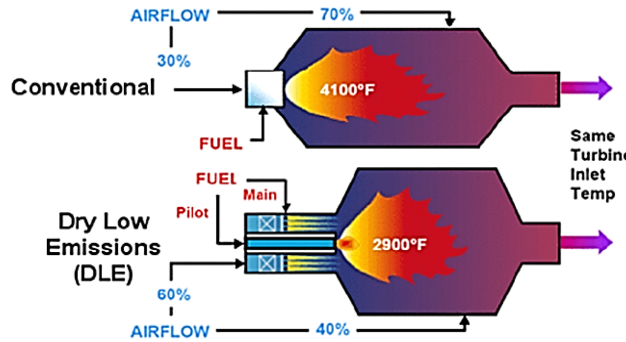

Figure 10: Flow in conventional gas turbine

5.2.3. Pulverized coal fired power stations

Available combustions processes utilized the trapped ventilation air as an ambient air in large power stations. According to the results of a pilot scale study in Australia at a power station for this technique this method is applicable for the power plants that can be built near mine sites [42].

Power stations are not generally found near gassy mines because it is not a suitable technique. Figure 11 shows a pulverized coal firing. Variation in the concentration of methane and flow rate of air can cause a negative impact on the operational performances of the equipment. For instance if during combustion the concentration of ventilation air increased it can damage the equipment, residuals and slagging [34].

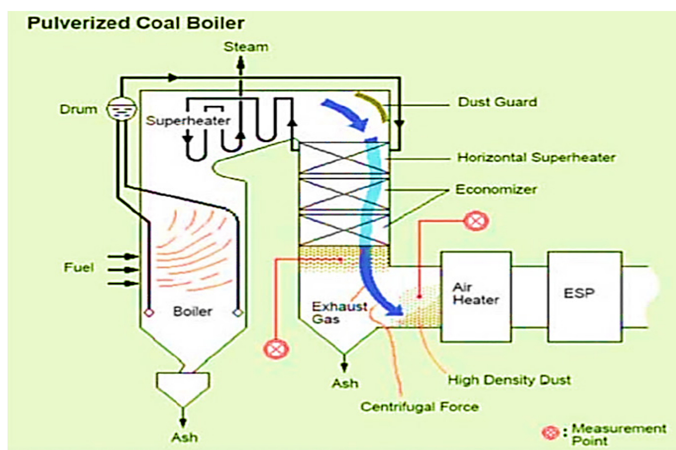

Figure 11: Schematic diagram of pulverized coal firing

5.2.4. Internal combustion engine

Medium quality gas is used by internal combustion engines to generate electricity so it becomes more beneficial to use ventilation air as ambient in the combustion. This technology has a low capital cost with the usage of minimum percentage of VAM. During the combustion process more NO_x is released because of high combustion temperature [42].

6. Conclusion

Anthropogenic emission of methane is about 17% from which 70% emission is just because of ventilation air emission from underground coal seams. As methane is supposed to be a great contributor of global warming but if it could be recovered and utilized it will become a great source of energy as well as this might be a beneficial reduction in greenhouse gases. As there are a number of technologies for methane mitigation and utilization but still some are non-operational due to absence of suitable and feasible operational parameters. Therefore recently more work is just on focusing the oxidation of ventilation air so as to get combustion energy for power generation. The following are some of the points that concluded the recent mitigation and utilization technologies according to their availability and possibility:

- As the drainage gas from pre and post mining can be used as source of energy but its usage totally depends on concentration of methane. While VAM has a large air to methane ratio and high flow it becomes more challenging to use it for energy production.
- Ventilation air methane from coal mine can be used as subsidiary and primary fuel in combustion processes for its abatement and utilization. Subsidiary uses are mostly for the reduction in greenhouse gas effect while primary fuel uses are not only for reducing greenhouse gas emission as well as for power generation.
- Adequate concentration of methane is necessary for effective utilization of VAM so concentrators are used to enrich methane to a sufficient amount (30%) so as to use beneficially for power generation through gas and conventional turbines.
- Mine site specifications are very important for utilization of ventilation air but if any installation occurs on mine site its investigation must necessary
- Oxidation of methane minimizes 95% of global warming effect while 67% of emissions are reduced.

Conflict of interest

The authors declare that there is no conflict of interests regarding the publication of this paper.

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Numerical Analysis of Drawdown in an Unconfined Aquifer due to Pumping Well by SIGMA/W and SEEP/W Simulations

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A B S T R A C T

In the present study a computer model of a pumping well has been developed and calibrated by using two slave programs of Geo-Slope software, i.e. (SIGMA/W and SEEP/W). The model has been used to study the behaviour of watertable and drawdown in an aquifer during pumping. SIGMA/W program was used to compute initial pore-pressure within an aquifer, while SEEP/W program was used to analyze the change in pore-pressure and drawdown during pumping respectively. From the results it is revealed that the vectors displaying the movement of the flow direction towards discharge well due to which decline in watertable occurs and a cone of depression and drawdown curve was formed. Comparison of the experimental and simulated data showed a good agreement among them. The drawdown line has been simulated for each concern depth and at each interval of time, which was further compared with the actual data for the computation of model efficiency. The performance of the model was evaluated on the basis of statistical parameters, i.e. mean error, root mean square error and model efficiency; these results are presented in Table 7. Statistical analysis of all the research data, i.e. RMSE, ME, R.E, and EF was found to be 0.134 m and 0.126 m, 3.05% and 98.86% respectively. Additionally verifiability of the model was also made by comparing observed and simulated values of observation wells (piezometeric heads); such graph is illustrated in Figure 5. The slope of the line was observed to be approximately at 45 degrees; thus the figure indicates no considerable difference between observed and simulated head values for all the observation wells. Consequently, it is concluded that simulated values of piezometeric heads are not much different than the observed ones. The results support the use of SIGMA/W and SEEP/W programs as a tool for investigating and designing pumping well practices.

1. Introduction

Large parts of the arid areas of Pakistan depend on canal and groundwater. Groundwater is used for drinking and domestic purposes meeting irrigation need, including livestock requirement and in industries. Groundwater also contributes to the environmental flows [1]. Understanding groundwater resources are important in developing responses to various groundwater problems such as groundwater depletion, and groundwater pollution. Groundwater basically occurs in aquifers in the pore spaces of fractures and other such opening in the rocks. Aquifers are saturated rocks or materials derived from rocks like sand and gravel capable of storing and transmitting water underneath the earth's surface [2]. Aquifers provide water to wells from there it can be pumped out. Open wells, bore wells and tubewells are man-made mechanisms used to extract a groundwater[3]. Aquifers also fed streams and rivers, especially during the dry season. Stream flows fed by groundwater are called as base flows. Aquifers may occur at relatively shallow depth below the ground surface and groundwater in such aquifers can be set to be at atmospheric pressure, such aquifers are called as unconfined aquifers.

Sometimes, aquifer occurs at much greater depth below the ground. Groundwater contained in such aquifers is at a pressure

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exceeding atmospheric pressure due to overlie and underlie rocks. Such aquifers are called as confined aquifers. The type of rock, its structure and especially the openings within decides how much water the rock will store and how quickly it will allow it to flow from one point to another within the aquifer. Pumping of groundwater from wells and the discharge to base flow cause aquifers to deplete [4]. Aquifers may sufficiently fill up again if wells have to sustain pumping for many years and streams must remain alive longer. This refilling of aquifer is called as groundwater recharge. Hydro-geological investigations are important in understanding the problems of groundwater over exploitation, quality, recharge and reuse.

Pumping tests provide the information regarding the storage and transmission properties of aquifers. These tests also indicate the capacity of a well to yield water. During the pumping test a well is pumped and water levels are measured in the pumping well as well as in specially made adjacent bore holes. The drop in water levels in an aquifer observed in these wells during pumping is called drawdown. The water level in a well fluctuates during drawdown and recovery is a response to the pumping in the well. Nowadays, many computer software's has come into general use, and any hard computations and simulation can be carried out through them by giving them appropriate inputs and data [5]. This results in less error frequency and more detailed analysis when compared with field observations. In order to simulate the water fluctuation process due to pumping through different soils regimes there are many numerical solution methods, i.e. Finite Differences (FDM), Finite Elements (FEM) and Boundary Elements (BEM) [6]. But the FEM is an effective numerical technique because of its numerous applied fields such as groundwater flow, multiphase flow, and mass flow through pours medium. The primary focus of this research work is to study the water level behavior in an unconfined aquifer due to groundwater movement caused by pumping through two slave programs of Geo-Slope i.e. SEEP/W and SIGMA/W for the development of numerical models and its analysis.

2. Objectives

The objectives of this research work were to compare the SIGMA/W and SEEP/W simulations of pore-pressure change in an unconfined aquifer caused by pumping with field observations, to compute the flow vectors, to analyze the movement of groundwater movement, and to simulate the drawdown curve for different time intervals.

3. Materials and Methods

3.1. *Location*

The study was undertaken in an area of Tando Soomro, which is 50 km away from Hyderabad, Sindh – Pakistan and containing homogeneous and anisotropic type unconfined aquifer located over an impervious layer in the year 2011-2012. The area receives irrigation water supplies through the canal system and also supplemented by groundwater supplies. The area has a number of fresh water tubewells meant for supplementing irrigation water requirement during surface water deficiency. The soil of the study area was mostly sandy loamy clayey up to 8 m depth, average ground surface level (elevation) with respect to MSL (Mean Sea Level) was 16m and watertable was around 3.77 m deep from the ground surface.

3.2. *Field Experiment*

In order to achieve the objective of the present research work a five year old data were depicted in this research. A field experiment was conducted by WAPDA during the year 2011 – 2012 to analyze the watertable behavior through the sandy loamy clayey soil. The experiment was conducted on a WAPDA installed tube-well (discharge well) along with 5 bore holes at a distance of 900 m, 1,800 m, 3,000 m, 4,800 m, and 5,100 m respectively. Before commencing the test, in preliminary step static water level within the pumping well and in all bore holes was recorded. The static water level is the non-pumping water level within the discharge well and borehole without the influence of pumping. After taking all the preliminary data before pumping the pump was then started and data collected at different intervals of time for discharge well and bore holes. As the study was conducted on constant discharge therefore, with the help of pump / valve discharge rates were kept as constant as possible throughout the research work till the pumping stopped. Finally, on the basis of results obtained from the experiment, it was utilized in developing numerical modeling and computations for different parameters were took place accordingly.

3.3. *Steps for Modeling*

In order to develop a 2- D finite element model, two slave programs of Geo-Slope Software i.e. (SEEP/W) for the flow analysis and (SIGMA/W) for the volume change analysis within the aquifer was used. A powerful and flexible feature in SIGMA/W has an ability to compute the volume change arising from an independently computed change in pore-pressure. Initially, by using SIGMA/W Insitu analysis a 2-D finite element mesh was generated to obtain the initial pore-pressure within the aquifer. The dimensions of the mesh were used for both SIGMA/W and SEEP/W programs to simulate the studied cases. The mesh is around 10,800 m long and 16 m in depth. The average ground elevation was 16m and the difference between the elevation of static watertable and ground surface was 3.77 m respectively. The domain is discretized into a mesh by 396 elements through placement of nodal points 479. The partially penetrating pumping well was then centrally assigned at a distance 5,400 m along with five adjacent bore holes on left and right side of the pumping well at a distance of 900 m, 1,800 m, 3,000 m, 4,800 m, and 5,100 m respectively. After the development of numerical model, the material properties for the materials used in subject mesh were calibrated. After calibration, it is then verified by the SIGMA/W software and computation for initial change in pore-pressure is carried out accordingly.

After the computation of initial pore-pressure within the aquifer the model was then imported to the SEEP/W program to find out the change in pore-pressure at different depths respectively. To solve the model numerically, initial and boundary conditions are specified first. In the present case, Neumann type boundary with the zero flux condition is executed on bottom, left and right of the mesh. Furthermore, Dirichlet boundary condition are assigned to the top of bore holes, while rest of the boundary nodes are treated as Neumann nodes with zero flux condition in such a way that the water level within the aquifer must remain at the initial watertable. After assigning the boundary nodes material properties for the materials used in subject mesh were calibrated and assigned accordingly.

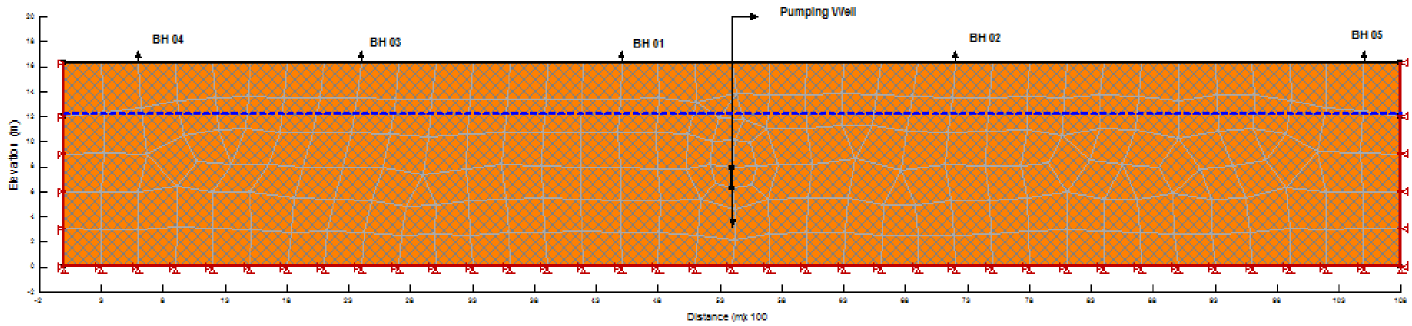


Figure 1: The mesh of the domain showing the boundary conditions for SIGMA/W analysis

With the objective to get precise results it has been assumed that the pumping will be controlled, so that the water level in the well will not drop below the top of the screen. H-type boundary condition i.e. (zero pressure) was then applied at the top of the well screen and which will increase hydrostatically with the depth within the well screen. Now as the starting and final pore-pressure conditions are known, therefore in order to find out the drawdown within the aquifer initial boundary conditions are required therefore, on the basis of experimental data the known boundary conditions was assigned to the pumping well for different interval of time accordingly. The time step sequence consists of 24 steps. Time starts by Zero minute and ends by 240 minutes for different depths in pumping well the drawdown in observation wells (bore holes) were recorded accordingly. Finally simulated results obtained from the SEEP/W and SIGMA/W program for each depth are compared with the observed data obtained from the experiment accordingly.

4. Results and Discussion

4.1. *FEM Mesh Formation and Its Verification*

The FEM mesh for the selected case is composed of four types of elements, i.e. triangular, square, rectangular and trapezoidal type of elements of 3 ft size (Figure 1). The domain is discretized into a mesh by 396 elements through placement of nodal point's 479. The material properties for subject mesh with proper dimensions are made as input to the SIGMA/W program and verification has been made accordingly. As the soil was mostly sandy loamy clay up to 8 m depth from the ground surface therefore, it is assumed that the complete soil region of the subject is to be considered as sandy loamy clay. The saturated hydraulic conductivities kx- and ky- are worked out as 3.455 x 10-4 m/s and 3.455 x 10-4 m/s, and the constant pumping rate of 0.042 m3/sec was adopted for the given aquifer. After assigning materials the initial watertable at 3.77 m from the ground surface was assigned accordingly. After all the necessary inputs, the computer program SIGMA/W verified the mesh development and delivered report that the vertical and horizontal meshing is strong enough and there is no error in formation of mesh model. Thus the model is ready for computation and analysis of the results.

Likewise, SEEP/W program is used to find out the change in pore-pressure at different depths respectively for the present case (Figure 2). According to the given conditions the Neumann type boundary with zero flux condition is executed on bottom, left and right of the mesh and Dirichlet boundary condition are assigned on the top of bore holes, while rest of the boundary nodes are treated as Neumann nodes with zero flux condition respectively. Then geological parameters and material properties are then calibrated accordingly. After all the necessary inputs, the computer program SEEP/W verified the mesh development and delivered report there is no error in formation of numerical model. Thus the model is ready for computation and analysis of the results.

4.2. *Analysis of Initial Pore-Pressure by SIGMA/W*

In order to solve the numerical model the initial pore-pressure conditions are required so that we can obtain the correct change in pore-pressures. Therefore, to study the behavior of drawdown in an aquifer due to pumping initially, SIGMA/W program was used to acquire the initial pore-pressure within the aquifer for (t = 0 minutes) Figure 3. The initial pore pressure computed from SIGMA/W was then used by SEEP/W to find out the change in pore-pressure at different depths respectively.

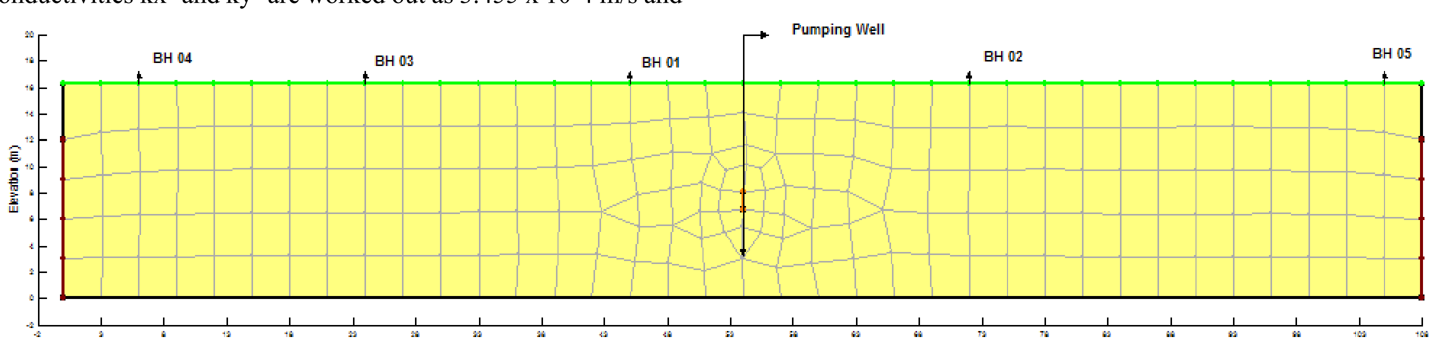


Figure 2: The mesh of the domain showing the boundary conditions for SEEP/W analysis

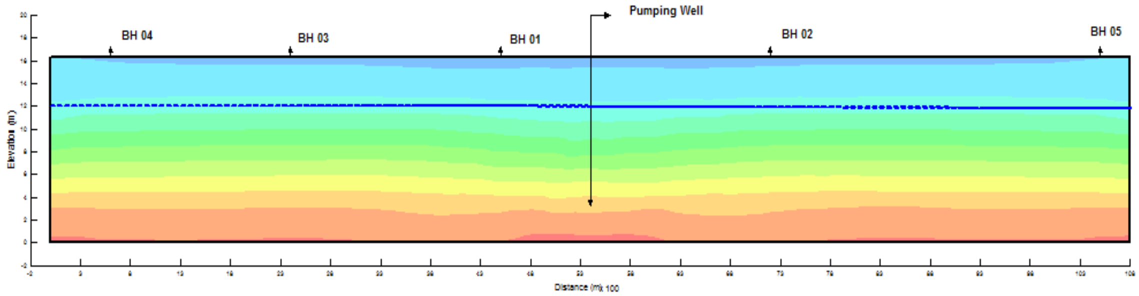
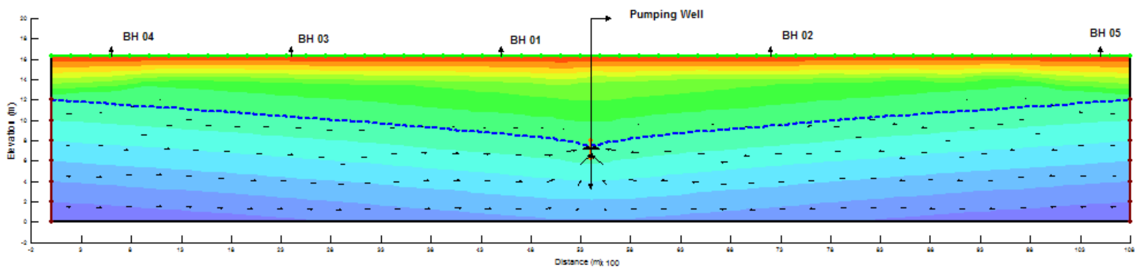


Figure 3: Initial Pore-Pressure within the Aquifer For (t = 0 minutes) by SIGMA/W



4.1: Drawdown at (t = 10 minutes) by SEEP/W Program.

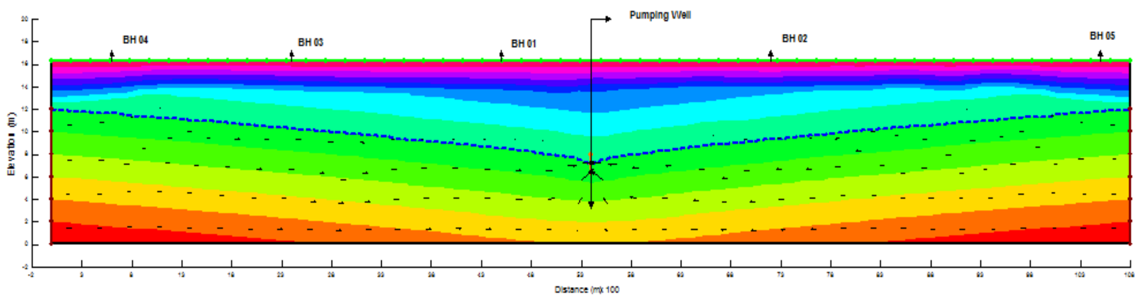


Figure 4.2: Drawdown at (t = 25 minutes) by SEEP/W Program.

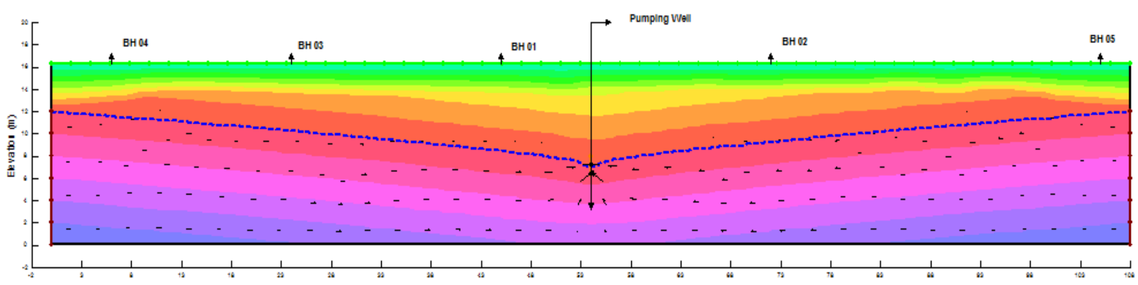
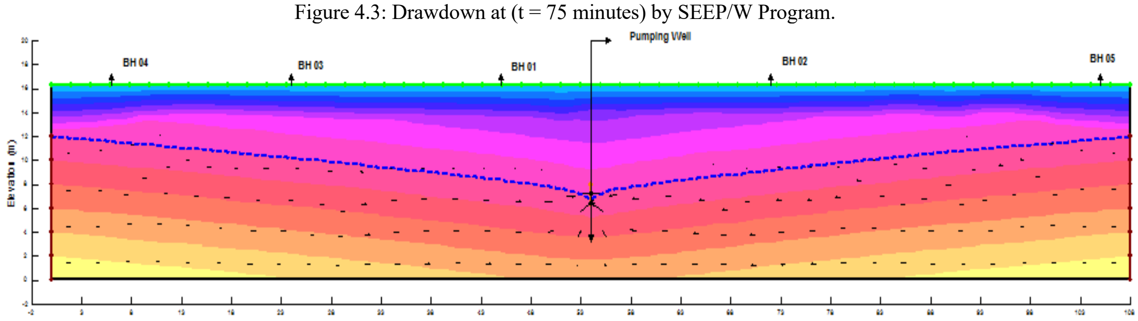


Figure 4.3: Drawdown at (t = 75 minutes) by SEEP/W Program.



: Drawdown at (t = 120 minutes) by SEEP/W Program.

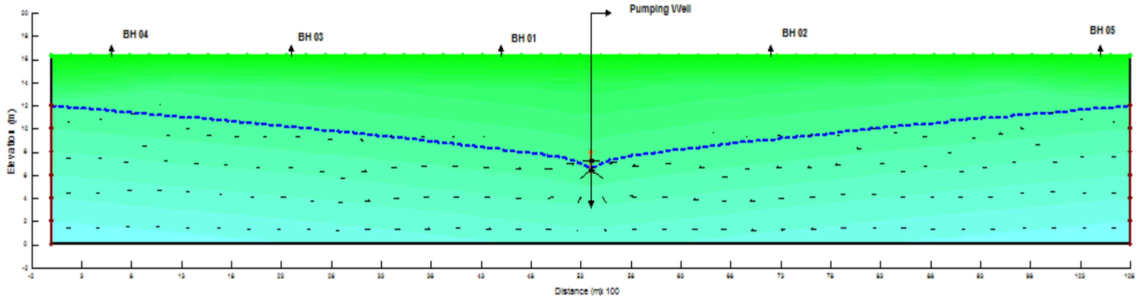
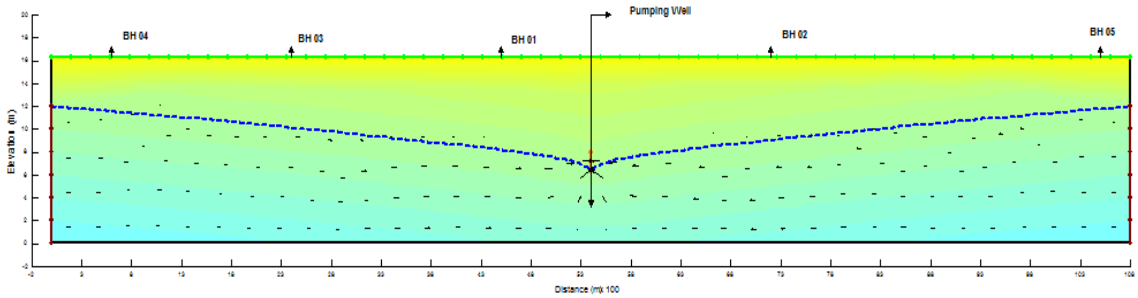


Figure 4.5: Drawdown at (t = 180 minutes) by SEEP/W Program.



: Drawdown at (t = 240 minutes) by SEEP/W Program.

The effect of the pumping is analyzed using a steady-state SEEP/W analysis. Boundary conditions are applied on the left and right ends, so that the water level remains at the initial watertable. Now as the initial and final pore-pressure conditions are known, the computation of drawdown in all five observation wells and analysis of the behavior of aquifer during pumping was conducted accordingly. The resulting long-term (steady-state) pore-pressure conditions are shown in Figure 4.1 - Figure 4.6.

Table 1. Observed Piezometeric Heads for Pumping Well Under Steady- State Conditions for an Unconfined Aquifer.

Date and Time	Elapsed Time	Elevation	Meter to Water	Drawdown Ho	Remarks
	Min	Meter	Ho	Do	
9:00 AM		12.23	3.77	0	Non-Pumping Level
9:15 AM	0	12.23	3.77	0	Pumping Started
9:17 AM	2	7.8	8.2	4.43	
9:19 AM	4	7.74	8.26	4.49	
9:21 AM	6	7.65	8.35	4.58	
9:23 AM	8	7.56	8.44	4.67	
10:00 AM	45	7.1	8.9	5.13	
10:15 AM	60	7.07	8.93	5.16	
10:30 AM	75	7.04	8.96	5.19	
10:45 AM	90	7.01	8.99	5.22	
11:00 AM	105	6.85	9.15	5.38	
11:15 AM	120	6.82	9.18	5.41	
11:30 AM	135	6.79	9.21	5.44	
11:45 AM	150	6.76	9.24	5.47	
12:00 PM	165	6.73	9.27	5.5	Afternoon
12:15 PM	180	6.64	9.36	5.59	
12:30 PM	195	6.61	9.39	5.62	
1:15 PM	240	6.52	9.48	5.71	Pumping Stopped

From Figures it is revealed that the water flow vectors are moving towards the pumping well due to which decline in watertable occurs and a cone of depression and drawdown curve was formed. The complete summary of results are elaborated in Table 1 – Table 6 respectively.

Table 2. Observed and Simulated piezometeric heads for Observation Well 01 under steady- state conditions at different interval of time.

Elapsed Time Min.	Meter to Water	Meter to Water	Drawdown	Drawdown	Remarks
Min.	Ho	Hs	Do	Ds	
	3.77				Non-Pumping Level
0	3.77				Started Pumping
2	6.68	6.83738	2.91	2.97856	
4	6.74	6.82625	2.97	3.00856	
6	6.83	6.99341	3.06	3.13459	
8	6.92	7.13037	3.15	3.24795	
45	7.38	7.55512	3.61	3.6963	
60	7.41	7.58633	3.64	3.72751	
75	7.44	7.61753	3.67	3.75871	
90	7.47	7.64874	3.7	3.78992	
105	7.63	7.80477	3.86	3.94595	
120	7.66	7.83621	3.89	3.97727	
135	7.69	7.80669	3.92	3.97754	
150	7.72	7.89908	3.95	4.03992	
165	7.75	7.91395	3.98	4.06274	Afternoon
180	7.84	7.9957	4.07	4.15011	
195	7.87	7.9943	4.1	4.16428	
240	7.96	8.14804	4.19	4.28922	Started Stopped

Table 3. Observed and Simulated piezometeric heads for Observation Well 02 under steady- state conditions at different interval of time.

Elapsed Time Min.	Meter to Water	Meter to Water	Drawdown	Drawdown	Remarks
Min.	Ho	Hs	Do	Ds	
	3.77				Non-Pumping Level
0	3.77				Started Pumping
2	6.2	6.34607	2.43	2.48725	
4	6.26	6.34018	2.49	2.52249	
6	6.35	6.5021	2.58	2.64328	
8	6.44	6.63606	2.67	2.75364	
45	6.9	7.06381	3.13	3.20499	
60	6.93	7.09502	3.16	3.2362	
75	6.96	7.12622	3.19	3.2674	
90	6.99	7.15743	3.22	3.29861	
105	7.15	7.31346	3.38	3.45464	
120	7.18	7.34488	3.41	3.48595	
135	7.21	7.31916	3.44	3.49001	
150	7.24	7.40773	3.47	3.54857	
165	7.27	7.42361	3.5	3.5724	Afternoon
180	7.36	7.50608	3.59	3.66049	
195	7.39	7.50666	3.62	3.67664	
240	7.48	7.65673	3.71	3.79791	Started Stopped

Table 4. Observed and Simulated piezometeric heads for Observation Well 03 under steady- state conditions at different interval of time.

Elapsed Time Min.	Meter to Water	Meter to Water	Drawdown	Drawdown	Remarks
Min.	Ho	Hs	Do	Ds	
	3.77				Non-Pumping Level
0	3.77				Started Pumping
2	5.05	5.16898	1.28	1.31016	
4	5.11	5.17563	1.34	1.35794	
6	5.2	5.32501	1.43	1.46619	
45	5.75	5.88672	1.98	2.0279	
60	5.78	5.91792	2.01	2.0591	
75	5.81	5.94913	2.04	2.09031	
90	5.84	5.98034	2.07	2.12152	
105	6	6.13637	2.23	2.27755	
120	6.03	6.16775	2.26	2.30882	
135	6.06	6.15112	2.29	2.32197	
150	6.09	6.23053	2.32	2.37137	
165	6.12	6.24883	2.35	2.39763	Afternoon
180	6.21	6.33302	2.44	2.48743	
195	6.24	6.33835	2.47	2.50833	
240	6.33	6.47963	2.56	2.62081	Started Stopped

Table 5. Observed and Simulated piezometeric heads for Observation Well 04 under steady- state conditions at different interval of time.

Elapsed Time Min.	Meter to Water	Meter to Water	Drawdown	Drawdown	Remarks
Min.	Ho	Hs	Do	Ds	
	3.77				Non-Pumping Level
0	3.77				Started Pumping
2	4.29	4.39107	0.52	0.53225	
4	4.33	4.37993	0.56	0.56224	
6	4.36	4.46317	0.59	0.60434	
8	4.4	4.52673	0.63	0.64431	
45	4.61	4.71549	0.84	0.85667	
60	4.64	4.75154	0.87	0.89272	
75	4.68	4.78759	0.91	0.92877	
90	4.71	4.82363	0.94	0.96481	
105	4.75	4.85968	0.98	1.00086	
120	4.78	4.89587	1.01	1.03694	
135	4.82	4.89385	1.05	1.0647	
150	4.85	4.96826	1.08	1.1091	
165	4.89	4.99399	1.12	1.14279	Afternoon
180	4.92	5.02263	1.15	1.17704	
195	4.96	5.03807	1.19	1.20805	
240	5.06	5.1841	1.29	1.32528	Started Stopped

Table 6. Observed and Simulated piezometeric heads for Observation Well 05 under steady- state conditions at different interval of time.

Elapsed Time Min.	Meter to Water	Meter to Water	Drawdown	Drawdown	Remarks
Min.	Ho	Hs	Do	Ds	
	3.77				Non-Pumping Level
0	3.77				Started Pumping
2	4.2	4.29895	0.43	0.44013	
4	4.23	4.28395	0.46	0.46626	
6	4.26	4.36125	0.49	0.50243	
8	4.29	4.41927	0.52	0.53685	
45	4.47	4.57931	0.7	0.72049	
60	4.5	4.61046	0.73	0.75164	
75	4.53	4.64161	0.76	0.78279	
90	4.57	4.67276	0.8	0.81394	
105	4.6	4.70392	0.83	0.84509	
120	4.63	4.73521	0.86	0.87627	
135	4.66	4.72957	0.89	0.90042	
150	4.69	4.79779	0.92	0.93863	
165	4.72	4.81899	0.95	0.96778	Afternoon
180	4.75	4.84301	0.98	0.99742	

195	4.78	4.85432	1.01	1.0243	
240	4.87	4.98427	1.1	1.12545	Started Stopped

4.4. *Model Validation*

Validation of any model is made by comparing predicted results against the field observations for the acceptability of the model. If the comparison shows a good coincidence, then the model developed can be recommended for practice. By comparing the overall average data pertaining to observed and simulated piezometeric heads for observation wells at different elevations and at different interval of time relative error was computed. Performance of any model is evaluated on the basis of statistical parameters. Following parameters that is mean error (ME), root mean square error (RMSE) and model efficiency (EF) are assessed [7]; their formulation is given below:

$$ME = \frac{1}{n}\sum_{i=1}^{n}(H_{si} - H_{oi}) \quad (1)$$

$$RMSE = \left[\frac{1}{n}\sum_{i=1}^{n}(H_{si} - H_{oi})^2\right]^{0.5} \quad (2)$$

$$EF = 1 - \frac{\sum_{i=1}^{n}(H_{si} - H_{oi})^2}{\sum_{i=1}^{n}(H_{oi} - H_{oa})^2} \quad (3)$$

Where;
H_{si} is the ith value of simulated head,
H_{oi} is the ith value of observed head, and
H_{oa} is the average or mean of observed head.

The EF is another parameter to evaluate the performance of the model. For the developed simulation model, RMSE and ME values are found to be 0.134 m and 0.126 m, respectively (Table 7) and the absolute maximum relative error amongst all the data sets is 3.05 %. Thus it is found that the performance of the model is good enough with model efficiency of 98.86 %. The compared results showed that experimental piezometric head readings are very close to the simulated readings; however some variation has been observed which may be due to personal errors. Consequently, it is concluded that simulated values of piezometric heads are not much different than the observed readings. Similar results were found for the computation of seepage quantity in an earthen watercourse using SEEP/W program [8] and for the analysis of phosphate movement through the sandy loamy clayey Soil by CTRAN/W Simulations [9] respectively.

Table 7. Summary of statistical parameters showing model performance

Statistical Parameters	**Values**
Mean Error (ME)	0.126 m
Root Mean Square Error (RMSE)	0.134 m
Model Efficiency (EF)	98.86 %
Absolute Maximum Relative Error	3.05 %

Additionally verifiability of the model is also made by comparing observed and simulated values of piezometeric heads; such graph is illustrated in Figure 5. The slope of the line is observed to be approximately at 45 degree; thus the Fig. indicates no considerable difference between observed and simulated head values for all the observation wells. Consequently, it is concluded that simulated values of piezometeric heads are not much different than the observed ones.

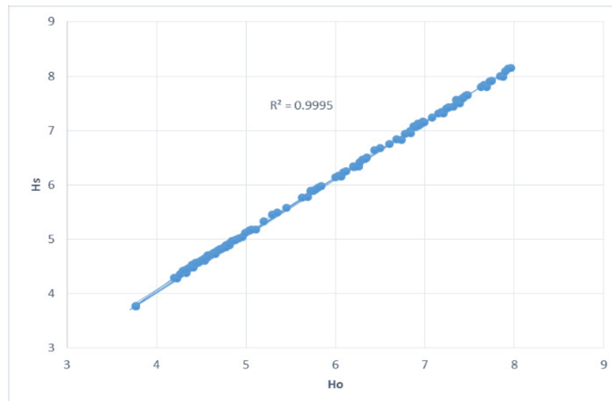


Figure 5: Relationship between observed and simulated hydraulic heads for Observation Wells.

5. Conclusions

In the present study a computer model for a pumping well (discharge well) based on FEM using two slave programs of Geo-Slope software i.e. (SIGMA/W and SEEP/W) has been developed and calibrated. The model has been used to study the behavior of watertable and drawdown in an aquifer during pumping. SIGMA/W program was used to compute initial pore-pressure within an aquifer, while SEEP/W program was used to analysis the change in pore-pressure and drawdown during pumping respectively. To achieve this objective five year old data was depicted in this research. A field experiment was conducted by WAPDA during the year 2011 – 2012 on a homogeneous and anisotropic type unconfined aquifer located over an impervious layer at Tando Soomro, which is 50 km away from Hyderabad, Sindh – Pakistan. The experiment was conducted on a WAPDA installed tube-well (discharge well) along with 5 bore holes at a distance of 900 m, 1,800 m, 3,000 m, 4,800 m, and 5,100 m respectively. The outcome of the research shows that the FEM model consistently yields accurate drawdown in contrast with field observation.

Initially, SIGMA/W program was used to acquire the initial pore-pressure within the aquifer for (t = 0 minutes). The initial pore pressure computed from SIGMA/W was then used by SEEP/W to find out the change in pore-pressure at different depths respectively. The effect of the pumping was analyzed using a steady-state SEEP/W analysis. Boundary conditions was applied on the left and right ends, so that the water level remains at the initial watertable. From the results it is revealed that the vectors displaying the movement of the flow direction towards discharge well due to which decline in watertable occurs and a cone of depression and drawdown curve was formed. Comparison of the experimental data and simulated data showed a good agreement among them. The drawdown line (phreatic line) has been simulated for each concern depth at each interval of time and compared with the actual data and the model demonstrates high efficiency and good fitness.

In order to counter-check the simulation results and to evaluate the performance of numerical model an observed piezometric head difference for all observation wells at different interval of time was finally compared with the simulated piezometric head accordingly. Statistical analysis of all the research data i.e. RMSE, ME, R.E, and EF to evaluate the performance of the model are found to be 0.134 m and 0.126 m, 3.05% and 98.86% respectively. The compared results showed that experimental piezometeric head readings are very close to the simulated readings; however some variation has been observed which may be due to personal errors. Consequently, it is concluded that simulated values of piezometric heads are not much different than the observed readings.

Additionally verifiability of the model is also made by comparing observed and simulated values of piezometeric heads; such graph is illustrated in Figure 5. The slope of the line is observed to be approximately at 45 degree; thus the figure indicates no considerable difference between observed and simulated head values for all the observation wells. Consequently, it is concluded that simulated values of piezometeric heads are not much different than the observed ones. The SIGMA/W and SEEP/W predictions of the pore- pressure distribution during pumping are found to be in very good agreement with the data. The results support the use of these programs as a tool for investigating and designing pumping well practices. Furthermore, as this software is adaptable in nature, therefore it can also be used to solve other types of problems i.e. seepage and slope stability in earthen dams; simulation of phreatic line in earthen dams and other hydraulic structures, modeling of lysimeters, sea water intrusion and other related issues, etc. It should to be introduce in universities and concern institution to gain knowledge about Finite Element modeling and software use.

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Effect of Foliar Application of Zinc on Growth and Yield of Guava (Psidium Guajava L.)

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In depth study focusing to ascertain the effect of different rates of Zinc (Zn) fertilization in improving the quality and yield of Guava fruit was carried out at Gharo, Sindh – Pakistan during year 2014-15. The outcome of the research revealed that there was no significant effect on the yield as well as quality, without using foliar Zn fertilizers. However, after application of the arrangement of foliar fertilizer the quality and production of fruits was significantly increased. The fruit yield in terms of plant height (3.111 m), length of fruit (6.989 cm), breadth of fruit (6.070 cm), weight of fruit (111.555 gm), number of fruits per plant (379.679), fruit yield (41.935 kg/plant) was recorded maximum in plants which were treated with Zn_5 (0.5%). Same treatment also showed the superior fruit quality traits evaluated in terms of TSS (9.373 %), Vitamin C (45.147 mg per 100 ml of juice), and Firmness (5.969 kg/cm^2) with lower acidity (0.485 %). Nearly same results were achieved by Zn_6 (0.6%) and Zn_7 (0.7%) treatments but statistically some parameters recorded less. However, plants with no foliar application showed un-satisfactory results regarding all the parameters. Too low or high concentration of Zinc solution may reduced the yield and yield parameters of guava.

1. Introduction

Crop yield in Pakistan is not satisfactory due to improper fertilizer management. Balanced nutrients are paid little attention. Its deficiencies emerge in the farmer's field and are recognized as the symptoms on foliage and reduction in the quality and yield. Foliar fertilizers are being used in vegetable and fruit crops that contain various macro and micronutrients [1]. This technology has come under use but is not common. Foliar Feeding is a technique for feeding plants by applying liquid fertilizer directly to their leaves. It is not a substitute for maintaining adequate levels of plant nutrients in the soil but can be beneficial in certain circumstances.

Most commonly, it is recommended for alleviating specific micronutrient deficiencies [2]. In recent years, products have been developed that contain growth hormones, natural plant sugars, microorganisms and other ingredients. The most effective means of foliar application is the use of spray equipment. Either low pressure or high pressure equipment may be used. Spray equipment provides better placement, less loss by dripping and more effective coverage of the foliage than most other methods of application [3].

The hose-end applicator may be used also. It does not provide as accurate coverage as the spray equipment does. It also results in greater loss of plant nutrients as it has a broader coverage than other types of spray. However, its lower cost, lower maintenance and ease of use often offset these disadvantages, especially for the home gardener [4]. For most fertilizer materials this is 2 to 4 pounds of the fertilizer in 100 gallons of water. Urea may be used at 12 lbs/100 gallons, sodium molybdate or molybdic acid at the rate of 2 lbs/100 gallons but only 4 to 8 ounces per acre of these are needed for plant growth. Borax or other Boron sources should be used at only 1 to 2 lbs/100 gallons of water. The chelate sources of iron, zinc, copper and manganese are used at 2 to 3 lbs/100 gallons of water. According to literature survey, many reports are available about foliar fertilizers on many plants as chrysanthemum, rose, tuberose and iris plants [9]. The present research was carried out to evaluate the impact of foliar application of Zinc on the growth, yield and development of Guava (Psidium Guajava L.).

2. Materials and Methods

Field experiment were carried out during 2014 and 2015 on a sandy loamy clayey soil at Gharo, Sindh – Pakistan. The soil moisture and temperature regimes at the site were Aridic and Thermic, respectively. An experiment was laid out in a complete Randomized Block Design with nine treatments and three replications. The existing guava plants (Allahabad variety) were studied in this research work and which were transplanted at a spacing of 6m x 8m during February 2009 on an area of 2 acres. The fruit trees were all planted at the same time and at the start of

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the experiment, they were more than 5 years old. The irrigation method was traditional flood irrigation throughout each year of the experiment. The water samples had been collected for the conductance of different water tests. Likewise, the samples of the soil were collected from different zones at 6 inch and 12 inch depth for different laboratory tests purposes on composite basis. The results of the soil and water samples are given in Table 1 and Table 2 respectively.

Table 1. Analysis Results of Soil (at 6 and 12 inch depth on composite basis)

Parameters	Test Results	
	Sample 01 (06 inch depth)	Sample 02 (12 inch depth)
pH at 25° C	8.07	8.12
EC	1.81 ds/m	1.91 ds/m
Nitrogen	87.76 mg/kg	83.3 mg/kg
Phosphorus	54.23 mg/kg	80.75 mg/kg
Potassium	95.12 mg/kg	119.01 mg/kg
SAR	1.41	0.422
Zinc	0.46 mg/kg	0.54 mg/kg

Table 2. Analysis Results of Water

Parameters	Test Results
pH at 25° C	7.55
EC	3.85 ds/m
SAR	7.97
$CaCO_3$ Hardness	852.90 mg/l
HCO_3	300.17 mg/l
TDS	2636.00 mg/lit

Chemical analysis of the irrigation water indicated relatively high salinity of the irrigation water with an ECw of 3.85 dS/m. Since, Guava is moderately salt tolerant and the soil texture was sandy loamy Clay throughout the profile, fruit production generally has been economical. Soil analysis of the experimental field indicated Zn deficiency. On the basis of results obtained the type and amount of fertilizers applied per tree were Urea (twice, 350 g each time), Triple Super Phosphate (300 g), and Potassium Sulphate (300 g) accordingly. The treatments provided to the plants in two split phases i.e. half dose after last harvest and half before the fruiting of upcoming guava yield in September.

Fertilizer applied between the radial distances 200 to 260 cm away from trunk, 15-25 cm deep and then properly covered with soil. There is no clear recommendation for Zn nutrition of Guava in the area and there is doubt about its efficiency under saline conditions. Zn was foliar applied thrice, using a pesticide application machine at different Zinc concentration i.e. Zn_0 (control – no Zinc), Zn_1 (0.1%), Zn_2 (0.2%), Zn_3 (0.3%), Zn_4 (0.4%), Zn_5 (0.5%), Zn_6 (0.6%), Zn_7 (0.7%) and Zn_8 (0.8%), when the branches had produced young leaves, in both years of the experiment. The source of Zn was dry zinc sulfate ($ZnSO_4$; 34% Zn). For recording the fruit quantity and quality observations five mature fruits were randomly selected from each observational plant and same fruits were used for recording the various physico-chemical properties of guava. The data were statistically evaluated by using SAS software. Duncan's multiple range test at 5% level of probability was used for comparison of means.

3. Results and Discussion

The subject research was carried out to check the fruit yield and growth rate of guava in a saline land conditions with the application of constant rates of NPK fertilizers along with different rates of Zinc fertilizer to all plants under study. The subject study revealed that guava plant height, length of fruit, breadth of fruit, weight of fruit, number of fruits per plant, fruit yield, TSS%, Acidity, Vitamin C, and Firmness differed very significantly between application of different rates of Zinc fertigation as mentioned in Table 3. The critical gathered observations and data for the above discussed parameters during the subject research are appended below:

3.1. Plant Height

Statistically remarkable results were observed for plant height with maximum 3.111 m and minimum 2.767 m in Zn_5 and Zn_1 respectively. Nearly same results for maximum height were achieved by treatments Zn_6 and Zn_7. The detailed results for all foliar application of zinc are given in Table 3. The study clearly implies that the increment in foliar application of zinc directly increases the plant height which means that they are directly proportional to each other. The present finding is in agreement with the findings of [7] in guava.

3.2. Length of fruit

Different rates of foliar application of zinc had a very positive effect on length of Guava fruit as shown in Table 3. From the obtained results it is clear that length of fruit increased with the increase in Zinc treatment rates. The length of fruit was maximum 6.989 cm for Zn_5 and minimum 6.272 cm for Zn_0 respectively. However, near about same results for maximum fruit length was achieved by Zn_6 and Zn_7 treatments. The present finding is in agreement with [12] in guava.

3.3. Breadth of fruit

Statistically considerable results were observed for breadth of fruit as shown in Table 3. Maximum 6.070 cm and minimum 5.222 cm for breadth of fruit were recorded in Zn_5 and Zn_0 treatments respectively. Once again for the breadth of fruit same observation was noted with COV 6.454 %. The discussed findings are in accordance with [8] in guava.

3.4. Weight of fruit

The application of proper plants nutrients can boost up the growth of guava plant which eventually increases the weight of fruits per plant accordingly. According to the obtained results it had been observed that maximum 111.555 gm weight per fruit were recorded in Zn_5 and minimum 80.689 gm weight per fruit were recorded in control Zn_0. The similar findings were also reported by [5] in guava.

3.5. Number of fruits per plant

During the research study it had been observed that maximum number of fruit 379.679 was noted in Zn_5, while minimum 295.970

fruits per plant was observed in Zn_0 (control). The detailed results for all foliar application of zinc are given in Table 3. Once again for the number of fruits per plant same observations were noted with COV 29.482% and SE $\pm$ 9.989 respectively. The present finding is in agreement with [11] for guava.

3.6. Fruit yield

On the basis of conducted study and statistical analysis of all harvesting operations it had been observed that foliar application of different rates of Zinc fertilizer had a positive effect on the yield kg / plant with COV 12.827% and SE $\pm$ 4.343 accordingly. Maximum yield was found to be 41.935 kg / plant when fertilized with treatment Zn_5. Likewise the minimum production was recorded in control 23.644 kg per plant for treatment Zn_0. The similar findings were also reported by [10] for guava.

Table3. Effect of different Zinc concentration on fruit quantity parameters of guava.

Treatment	Plant Height	Length of Fruit	Breadth of Fruit	Weight of Fruit	Number of fruits per plant	Fruit yield
	m	cm	cm	gm		kg / plant
Zn_0	2.767	6.272	5.222	80.689	295.970	23.644
Zn_1	2.778	6.333	5.414	86.618	315.039	27.018
Zn_2	2.808	6.393	5.616	88.234	326.260	28.502
Zn_3	2.858	6.464	5.686	90.597	334.845	30.037
Zn_4	3.111	6.989	6.070	111.555	379.679	41.935
Zn_5	3.091	6.595	5.939	107.929	351.046	37.511
Zn_6	3.070	6.595	5.808	100.960	335.552	33.542
Zn_7	2.990	6.464	5.737	93.021	336.764	31.017
Zn_8	2.909	6.464	5.737	90.708	338.956	30.441
SE(m)$\pm$	0.172	0.253	0.212	10.878	9.989	4.343
LSD ($p<0.05$)	NS**	NS**	NS	NS	NS	NS
COV(%)	9.817	6.706	6.454	12.938	29.482	12.827

* Means followed by different letter shows significant result at 5% level of significance.

3.7. Fruit Quality Parameters

The chemical fruit quality in terms of maximum total soluble solids 9.373%, minimum acidity 0.485%, Vitamin C (45.147 mg per 100 ml of juice) and firmness 5.969 kg/cm^2 were recorded with treatment Zn_5 whereas, lowest total soluble solids 9.080%, maximum acidity 0.586%, Vitamin C (25.078 mg per 100 ml of juice) and firmness 3.808 kg/cm^2 were recorded in treatment Zn_0 control. These results are in accordance with [6] and [11] in Guava.

Table 4. Effect of different Zinc concentration on fruit quality parameters of guava.

Treatment	Fruit Quality Parameters			
	TSS	Acidity	Vitamin C	Firmness
	%	%	(mg per 100 ml of juice)	kg /cm^2
Zn_0	9.080	0.586	25.078	3.808
Zn_1	9.312	0.545	28.846	4.767
Zn_2	9.474	0.515	30.250	4.515
Zn_3	9.242	0.495	27.593	5.020
Zn_4	9.373	0.485	45.147	5.969
Zn_5	9.332	0.566	25.078	4.737
Zn_6	9.575	0.495	43.895	4.959
Zn_7	9.534	0.475	37.623	4.747
Zn_8	9.373	0.566	35.108	4.141
SE(m)$\pm$	0.364	0.495	4.646	2.121
LSD ($p<0.05$)	NS	NS	NS	NS
COV(%)	6.656	20.432	24.371	33.754

* Means followed by different letter shows significant result at 5% level of significance.

4. Conclusions

The subject study clearly pointed out that Zinc foliar application remarkably increase the yield and quality of Guava fruit. Amongst different concentration of Zinc, Zn_5 (0.5%) was observed to be more suitable and economical dose as the fruit yield in terms of plant height (3.111 m), length of fruit (6.989 cm), breadth of fruit (6.070 cm), weight of fruit (111.555 gm), number of fruits per plant (379.679), fruit yield (41.935 kg/plant) was recorded maximum. Same treatment also showed the superior fruit quality traits evaluated in terms of TSS (9.373 %), Vitamin C (45.147 mg per 100 ml of juice), and Firmness (5.969 kg/cm2) with lower acidity (0.485 %). Nearly same results were achieved by Zn_6 (0.6%) and Zn_7 (0.7%) concentration but statistical some parameters recorded less.

However, control plants showed un-satisfactory results regarding all the parameters. Too low or high Zinc concentration can reduced the yield and yield parameters of guava. From the obtained statistical results it can be concluded that the 0.5% micro-nutrient Zinc solution concentration has a best suited dose to increase the Guava yield in the arid region of Gharo, Sindh – Pakistan. However, further investigation is necessary to establish the present findings in other regions of Pakistan with Guava and other fruits.

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Chemical and Different Nutritional Characteristics of Brown Seaweed Lipids

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ABSTRACT

Lipids are the fatty acid or their derivative which are insoluble in water but soluble in organic solvent. Brown color seaweeds have high value of total lipids (TL) contents, ranging from 10 to 18 % of dry weight. It contains glycoglycerol lipids (GL) as lipid class, which is rich in 18:4n_2, 20:5n_2 and 20:4n_5. Brown colored seaweed also contains fucoxanthin as a main functional compound. Its stable nature of oxidation is due to the presence of polyunsaturated fatty acids (PUFAs). Oxidative stability of brown seaweeds is very high. They also show ant obesity and anti-diabetic effects.

1. Introduction

Algae can be divided into two main groups, macro-algae (seaweeds) and micro-algae. Approximately 9000 seaweed species are available worldwide, which are further divided into three main groups on the basis of their pigmentation: brown (Phaeophyta), red (Rhodophyta) and green (Chlorophyta) seaweeds. Whole parts of seaweed are available for effective biomass sources because of their high rate of absorption of carbon dioxide from the atmosphere.

Seaweeds have been used as sources of food, medicine, cosmetics, fertilizer, feed and bio-energy [1-3]. Seaweeds are enriched in non-starch polysaccharides food components such as carrageenan and alginate, which cannot be degraded by mammalian enzymes [4]. These contain high content of amino acid then the other vegetable. These are also enriched in polyphenols, especially phlorotannins which is used as an antioxidant. Although lipid content in seaweed is lower than marine fish but due to their large stock in coastal waters define it as potential source of functional lipid. Lipid content in oily fish has been reported to be approximately 20 wt. % per dry weight (DW), occasionally reaching 50 wt. % per DW, but seaweeds contain up to 1–5 wt. % total lipids per DW. [5,6]. On the other hand, recent research revealed that contents of TL and omega-3 polyunsaturated fatty acids of seaweeds fluctuate seasonally, it could reach 15 % TL per DW and could contain over 40 % omega-3 PUFAs per total fatty acids.

Several types of bioactive compounds, such as omega-3 PUFAs, omega-6 arachidonic acid, fucoxanthin, fucosterol and some polyphenols are present in brown seaweeds. Carotenoid which is found in brown seaweeds shows several physiological effects due to their unique molecular mechanisms [7].

2. Seaweed lipids

The lipid content in seaweed is very sensitive and remarkably change by species to species, it also varies by geographically, seasonally, temperature, salinity and light intensity [8].

A latest research revealed that species of tropical areas have significantly Lower lipid contents than the cold area species. A quantitative lipid analysis showed that the TL content in Sargassaceae (a major brown seaweed family) was higher in subarctic zones (approximately 6 % per DW) than tropical zones (0.9–1.9 % per DW) [9, 10].

3. Brown seaweed lipids

Seaweeds play a vital role in preserving coastal belt ecosystems especially brown seaweeds [11,12]. In Japan brown seaweeds are form a part of the staple diet. They contain valuable nutrients and bioactive components, which is not found in terrestrial plants. Major membrane lipid is also present in brown seaweeds. The composition of fatty acid of the chloroplast Glycoglycerol lipids is rich in highly unsaturated fatty acid. The main fatty acid in the GL of plant leaf is alfa linolenic acid (LNA), which is rich in monogalactosyl-diacylglycerols (MGDG), digalactosyl-diacylglycerols (DGDG), Stearidonic acid (SDA), arachidonic acid (ARA) and eicosapentaenoic acid (EPA). These are the major fatty acids in seaweeds [13, 14]. A clinical study expresses about the omega-3 PUFAs that it has important cardio-protective effect [15] and the reduction of cardiovascular disease (CVD) occur by taking of EPA and

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docosahexaenoic acid (DHA) [16,17]. ARA, the active form of omega-6 PUFA, is found help ful to develop immune response, thrombosis and brain function. ARA and DHA are also useful for neuro development of infant so it should be used in diet supplement. ARA and DHA are major constituents of cell membranes and play an important role in the structure of neurons in the central nervous system, where these are present at high concentrations [18]. Humans have a poor ability to form DHA from LNA or ARA from linoleic acid (LA) due to the low activity of delta-6 desaturase. Brown seaweed lipids contain fucosterol and fucoxanthin as functional components. Fucoxanthin exhibits characteristic biological activity, including anti-obesity [19], anti-diabetic, antioxidant and anti-cancer effects. The physiological effects of fucoxanthin have been described in detail in several reviews [20, 21].

4. Seaweed lipids Oxidative stability

Due to large number of double bonds, the major PUFAs in brown seaweed lipids, such as SDA are very easily oxidized [22,23]. Oxidative deterioration of these PUFAs is one of the very important problems in food chemistry, as lipid oxidation produce undesirable flavors, odor and lower nutritional quality and storage of lipid-containing foods. Carotenoids are degraded by carotenoid–radical inter actions and cleavage at the center of the carotenoid bone. The electron-rich status of fucoxanthin makes it less stable than other carotenoids. Thus, the low stability of fucoxanthin may be a major problem in the application of brown seaweeds to food materials as fucoxanthin resources.

5. High oxidative stability of PUFAs as GL form

GL plays an important role in photosynthesis. It is very rich in omega-3 PUFAs such as SDA, EPA and LNA. The content of these PUFAs increases with the increase of photosynthetic activities [24]. The GL of chloroplast is always exposed to oxidative stress because it has high level of PUFAs and light energy absorption for photosynthesis. Reactive oxygen species (ROS) are developed in the photosynthetic membrane. This can cause oxidative damage to many cellular components, including proteins, lipids membrane, nucleic, chlorophyll and nucleic acids. To maintain the level of ROS and to save the cells, seaweeds possess a number of antioxidants (phenolic , ascorbate, glutathione compounds, carotenoids and tocopherols) and enzymes (Catalase, Superoxide dismutase , Glutathione reductase and Ascorbate peroxidase) to scavenge the ROS and to regenerate the active forms of antioxidants [25,26]. A latest research showed that PUFAs in GL form has high oxidative stability [27]. GL also showed higher oxidative stability than Soybean oil. It is due to the protective effect of sulfoquinovosyl and galactosyl moieties on PUFAs bonded to the same GL molecule. If we want to decrease in the oxidative stability of food lipids we should also use carbohydrates [28].

6. Brown seaweed lipids Nutritional impact

Brown seaweed lipids have up to 5 % fucoxanthin [10]. Fucoxanthin shows Anti-obesity effects [19]. It also improves insulin resistance and remarkably decreases blood glucose level [29]. A research shows that when brown seaweed lipids are given to obesity/ diabetes model mice, excess fat accumulation in abdominal white adipose tissue (WAT) is gradually reduced, and glucose levels are again restored to normalize levels, mainly due to presence of fucoxanthin in the lipids.

It is also observed that a combination diet of 0.1 % fucoxanthin and fish oil also markedly decrease the blood glucose and plasma insulin quantity to the same levels. But omega-3 fish oil alone had very little effect on Abdominal WAT weight and plasma glucose level, as brown seaweed lipids contain high levels of omega-3 PUFAs, so the effect of fucoxanthin will be greater compared with that fucoxanthin alone. Another research shows that when brown coloured seaweed lipids were given to Animals, a significant increase in the component of DHA and ARA of the liver was also observed [7].

7. Conclusion

The brown seaweed families *Laminariales* and *Fucales* are two basic species, forming underwater forests which provide and develop different ecological services and effect to coastal belt ecosystems. They are also a major class of aqua cultured seaweeds and are regarded as having significant potential to serve as a biomass source. The brown seaweeds contain polysaccharides, including undigested fibers, minerals, proteins and lipids. Although the lipid content of brown seaweeds is less than the content of other nutrients, it contains biologically active compounds, such as fucoxanthin, omega-3 EPA and SDA and omega-6 ARA. Among these compounds, fucoxanthin is major to understand the characteristic functionality of brown seaweed lipids. The oxidative stability of PUFAs is occasionally problematic in the application of marine lipids to food and other products. A research study indicated the high oxidative stability of omega-3 PUFAs in brown seaweed lipids. Although more research study will be needed to confirm this characteristic oxidative stability of PUFAs in brown seaweed lipids, these lipids may be applied to nutraceuticals and functional foods as an oxidative stable omega-3 source. For the commercial use of brown seaweed lipids, a search for TL-rich seaweed materials will be important. Studies on the seasonal, regional and species variations of lipid components showed that several brown seaweed species collected in the growing stage had high levels of TL, fucoxanthin and omega-3 PUFAs.

Conflict of interest

The authors declare that there is no conflict of interests regarding the publication of this paper.

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