MICROALGAE- A PROMISING TOOL FOR SUSTAINABLE FUTURE

Abstract

With the world directing towards accomplishing the Sustainable Development Goals (SDGs) under the United Nations 2030 agenda to protect the planet and improve lives and prospects of everyone, everywhere, biological entities are being explored extensively to achieve them. While studies of microalgal applications for sustainable development have been carried out in the past, their interest have been rising in every sector including remediation of environment, food and fodder production, pharmaceuticals, cosmetics, biofertilizers, plastic degradation, bioplastic production and even biofuel production. Microalgae are the organisms capable of performing photosynthesis and are found in various terrestrial to aquatic including marine habitats**.** The ability of microalgae to consume CO_2 and produce a wide range of active compounds such as carbohydrates, lipids, proteins, pigments, vitamins, fatty acids, polysaccharides and antioxidants has led to their increasing implication as a tool for a sustainable future. This article discusses the prospects of application of micro algae, present trends and futuristic approach capable of leading towards a better environment and a sound future.

Keywords: Microalgae, Bio prospects, Bibliometric analysis, VOS viewer software.

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I. INTRODUCTION

Algae are a diverse group of autotrophic photosynthetic organisms, which are among the primary producers in the aquatic ecosystems capable of fixing CO_2 into carbohydrates during photosynthesis (Haddad et al., 2014**).** They may be simple unicellular microscopic motile or non-motile, to complex branched macroscopic forms. Algae are ubiquitous in distribution and can be found in every possible habitat including marine and fresh water bodies (Desikachary, 1959).From 30,000 to over 1 million algal species are thought to exist in this world playing a vital role in functioning of both freshwater and marine ecosystems(Guiry, 2012). Among which, microalgae are the most diverse algal group existing in a broad variety of forms, sizes and shapes.

Despite being microscopic, the broad adaptability and potential advantages of microalgae have led to theirs urge in recent years in the field of research and sustainable development. Being cosmopolitan, these microorganisms are excellent for investigation by ecologists, phycologists, biochemists, microbiologists as well as bacteriologists. Researchers are constantly looking for new beneficial applications of these microscopic organisms to develop novel technology and harness their potential for a healthier and better sustainable future.

Keeping the ideas above in mind this communication deals with all the aspects related to microalgal bio prospects and its potential scope in the near future through VOS (Visualization of Similarities) viewer software.

II. BIO PROSPECTS OF MICROALGAE: PAST, PRESENT AND FUTURE

As a result of their numerous inherent benefits, algae have recently attracted a lot of attention for bioprospecting (Teronpi and Baruah 2017). Algae are one of the primary natural suppliers of a wide variety of beneficial substances, including antibiotics, proteins, carbohydrates, lipids, chlorophylls, carotenoids, phycobilins, glycolipids, phenolics, terpenes, β-diketone, polyols and indole alkaloids (Pratt et al., 1944; Ördög et al., 2004; Del Campo et al., 2007; Subudhi, 2017; Karkala et al., 2021). For which algae are being widely used in fish and animal feedstock, agricultural industry, neutraceutical andpharmaceutical industry, cosmetic industry and also are considered for biofertilizer, bio plastic and biodiesel production for sustainable environmental management (Fig 1) (Apt and Bahrens, 1999;Soletto et al., 2005;Spolaore et al., 2006; Milledge, 2011; De Jesus et al., 2013: Mullue et al., 2023). Algal species belonging to the genera *Anabaena, Nostoc, Botryococus, Chlamydomonas, Chlorella, Haematococcus, Scenedesmus,* have been well known source of vitamin precursors, antioxidants, immune system boosters, anti-inflammatory agents, beta-carotene, lutein, astaxanthin and polyunsaturated fatty acids and have already been utilized for production of commercial products (Stranska-Zachariasova et al., 2016; Mullue et al., 2023).

Microalgae have also been known to produce various metabolites showing antiviral and antifungal properties. Lectincyanovirin-N, isolated from the cyanobacterium *Nosto cellipsosporum*, has shown antiviral action against the ebola, influenza, and HIV viruses (Mullue et al., 2023). Astaxanthin is another potent antioxidant extracted from the green alga *Haemat ococcus pluvialis* (Plaza et al., 2009).Short chain fatty acids extracted from *Haemat ococcus pluvialis* have also presented strong antibacterial property against Vibrio strains (Subudhi, 2017). Green microalgal genus Chlorella produces chlorellin, an antibacterial substance that can prevent the growth of both Gram-positive and Gram-negative bacteria (Little et al., 2021). Chlorellin has been extracted from the algal species *Chlorella vulgaris*. Calothrix A, an alkaloid isolated from the cyanobacteria Calothrix, has demonstrated to possess antibacterial property against *Bacillus subtilis* (Doan et al., 2001). *Spirulina a*nd *Chlorella vulgaris* are primarily used and exploited in the market for the manufacture of Single Cell Proteins (SCP) (Karkala et al., 2021). The green alga *Botryococcusbraunii* produces allopathic substances viz. mixture of free fatty acids containing α-linolenic, oleic, linoleic, and palmitic acids. These fatty acids can become hazardous to other group of phytoplanktons,facilitating its dominance in the habitat (Bacellar-Mendes and Vermelho 2013). *Scytonema*, a cyanobacterial genus can be exploited for production of cyanobacterin, a chlorinated γ-lactone that specifically inhibits a variety of microalgae, including cyanobacteria and green algae, at micromolar concentrations (Mason et al., 1982).

For many industrial uses, microalgae-based biofuelshave been acknowledged as a feasible substitute for fossil fuels (Gong and Jiang, 2011). Researchers recommend that microalgae *Botryococcus braunii* and *Scenedesmus dimorphus* can be used as raw materials for production of biofuels (Nagaraja et al., 2014; AroneSou raj et al., 2016; Tasic et al., 2016; Prathima and Karthikeyan 2017; Dilia et al., 2018). It has also been demonstrated that *Bot ryococcus braunii* is a potential candidate for bioremediation of domestic waste water as it can reduce ammonia, potassium, electrical conductivity and TDS from waste water (AroneSou raj et al., 2016).

Figure 1: Bio prospects of microalgae in different aspects

III. RECENT TRENDS OF MICROALGAL APPLICATION

1. **Heavy metal (HM) remediation:** Microalgae are found to grow in harsh environment and they adsorb the noxious substances available therein. One of the toxic elements present in such environment is the HMs like cadmium (Cd), arsenic(As), lead(Pb), mercury (Hg), zinc (Zn), copper (Cu), iron(Fe), manganese (Mn), nickel (Ni), chromium

(Cr) etc. which are increasing in nature day by day(Kalita and Baruah, 2023).These HMs effects the aquatic and land ecosystem by incorporating in the food web.

Microalgae are the eco-friendly tools to remediate these harmful substances for a better and healthier future. Microalgal members like *Oscillatoria princeps*(Sulaymonet al., 2013), *Spirulina maxima*(Gong et al., 2005), *Aulosira fertilissima* (Singh etal., 2007), *Chlorella vulgaris*(Sandauet al., 1996; Klimmeket al., 2001; Ferreira et al., 2011), *Scenedesmus obliquus*(Monteiro et al., 2011), *Microcyst* is sp. (Singh et al., 1998), *Pithophora odeogonia*(Singh et al., 2007), *Spirogyra hyalina* (Kumar and Oommen, 2012) could remove a number of toxic heavy metals from the environment in a variable pH and temperature ranges (Kumar et al., 2015). They possess a number of functional groups in their cell wall that are known to be involved in the metal uptake process (Kalita and Baruah, 2023). Electrostatic interaction between metal ions and the respective functional groups is critical for successful metal homeostasis. Once the metal ions are adsorbed onto the cell surface the live cells thereby activate the metabolically dependent active processes and transport the ions into the cell organelles. Mitochondria, chloroplast, vacuoles and poly p bodies are the organelles that are specifically involved in active transport during metal accumulation; while the non-living microalgal biomass are restricted to only adsorption mechanism.

2. **Biofuel Production:** Microalgae are abundant in lipids content and can be used to make biofuels like biodiesel, which are more eco-friendly substitutes for fossil fuels(Teronpiet al., 2021). Particularly,Triglyceride content in microalgae is the main source for the production of biofuel. On the other hand, biomass can be thermochemically transformed into biofuel oil (Lestari et al., 2009). Production of biofuel from microalgae has the potential to lower greenhouse gas emissions and lessen reliance on limited fossil fuel supplies. Among all the members of the microalgal group, chlorophycean members are rich in lipid content (Patidar et al., 2015) and it could be attributed to the production of biofuels. *Chlorella emersonii, Chlorella protothecoides, Schizochytrium limacinum, Scenedesmus obliquus* are the few members of chlorophycean members which are known for their rich lipid content (Suali and Sarbatly, 2012).

3. **Plastic degradation:** In general, plastics are regarded as synthetic or semi-synthetic materials or polymers, which although easy to use, but pose a threat to the environment. Conventional plastics affect the environment because they are produced from crude oil, a finite natural resource and do not decompose through bacterial decomposition, landfills merely store them for decades; and their combustion emits poisonous chemicals (Abdo and Ali, 2019). PVC (polyvinyl chloride), PE (polyethylene), PP (Polypropylene), PET (Polyethylene Terephthalate), LDPE (Low-Density Polyethylene), HDPE (High Density Polyethylene) are the most commonly used plastic compound in recent years.

   Researchers have introduced a number of microbes including a few microalgae for the degradation of this polymeric substance. Algal specieslike *Scenedesmus dimorphus,Oscillatoria subbrevis, Phormidium* lucidum, *Navicula* pupula and *Anabaena spiroides* are known to degrade PE (Sarma and Rout, 2019). Amongst those a for e mentioned species *Anabaena spiroides, Scenedesmus dimorphu*s, *Navicula pupula* are known to degrade both HDPE and LDPE. Recently, *Nostoc carneum* has gained attention for the degradation mechanism of LDPE (Sarma and Rout, 2020).

4. **Bio plastic production:** Plant-based components such as naturally occurring polymers (carbohydrates, proteins, etc.), along with other tiny particles (sugar, disaccharides, and fatty acids) can be utilized to make bioplastics. Bioplastics capacity arose from roughly 2 million tons in 2014 to approximately 6.7 million tons in 2018, with the majority of them being manufactured from starch and poly (lactic acid) (PLA)based polymers.

   In order to reduce the plastic pollution researchers have developed bioplastics from different natural sources including microalgae. Certain microalgae species have the potential to replace the synthetic polymers with biodegradable bioplastics as an ecofriendly substance. Microalgae are rich in carbohydrate and protein content, which serve as a core agent for production of bioplastics (Chia et al., 2020). Cellulose, Starch, PE, PVC, PHA(Polyhydroxyalkanoates), PHB(Polyhydroxybutyrate), PLA and polymers based on protein are a few examples of chemicals from algal biomass that are being used to create biodegradable plastics. PHA is the polymer that is most frequently suggested for use in the production of bioplastics since it can be broken down by enzymatic action. Additionally, PHB, a subtype of PHA, has recently become a novel polymer for the production of bioplastics due to its effective oxygen barrier (Karan et al., 2019).

5. **Bio fertilizer:** A number of micro-organisms, plants and animals are known to the researchers and farmers that can be used as fertilizers as an alternative to chemical fertilizers (DasGuptaet al., 2021). Microalgae can be used as a biofertilizers because of their ability to fix atmospheric nitrogen, boost soil fertility and promote plant growth and development. Certain microalgae, such as cyanobacteria, have the potential to fix atmospheric nitrogen into ammonia (Mishra and Pabbi, 2014), which is easily available to plants and could absorb very quickly and eventually help in plant growth and development.Nostoc sp., Anabaena sp., Spirulinaplatensis are known members of cyanobacteria which has gained attention for their high nitrogen fixing capacity. In such mechanism heterocyst (an organelles in cyanobacteria) solely play the key role in ammonia synthesis and nitrogen fixation (R. Banemann, 1979). In recent years a few chlorophyean members like *Chlorella vulgaris, Acutodesmus dimorphus* also known for their effective results in growth and development in many occassions (Gomieroet al. 2011; Kim et al., 2014; Bumandalaiet al., 2019).

   Apart from this, microalgae are known for their high content of trace elements, including phosphorous and calcium contents which enhance soil fertility. The organic elements also increase the water-holding capacity and augment soil building and health. The presence of active compounds such as phytohormones like auxin, cytokinins, and gibberellins and the occurrence of few antimicrobial properties make them suitable biofertilizers (Alvarez et al., 2021). Phytohormones such as indole 3-acetic acid, Indole butyric acid, Indole-3-propionic acid, Zeatin, and kinetin have been reported from various members of microalgae viz. *Nostoc* spp., *Anabaena* spp., *Aphanothece* sp. 515 MBDU, *Scenedesmus armatus, Chlorella pyrenoidosa*, *and Scenedesmus obliquus* (Renuka et al., 2018). Therefore, it can be remarked that the use of such microalgae in crop fields shall enhance crop productivity and yield.

6. **Food and Fodder:** For thousands of years, algae have been a part of human diet across various regions of the globe (Aaronson, S. 1986). While these algae are mostly macroalgae such as *Porphyra, Gracilaria, Palmaria palmata, Lamina japonica, Ulvalactuca, Codium* etc., various micro algae have also found their way into human diet including *Spirulina spp., Nostoc commune, Chlorella spp., Dunaliella salina and Haematococcus pluvialis* (Borowitzka, 1998; Baruahet al., 2014; Wu et al., 2022).These algae are eaten fresh, dried, pickled as well as in backed forms with delight. Loaded with compounds such as carotenoids, amino acids, vitamins, antioxidants, lipids, fatty acids and carbohydrates etc., algae are being used today in food industries extensively as food supplements (Wells et al., 2016). Algae have also been used to enrich meat products, fish products, cereal products and produce fermented products (Ścieszka andKlewicka, 2018, Hung et al., 2021).

   As a feed source, microalgae have been used in hatchery for farmed shellfish, finfish as well as other species grown commercially. Algal species are cultivated separately and regularly administered into these aquacultures (Shields and Lupatsch, 2012). Numerous studies have been carried out to study the application of various algal stains, their nutritional composition, techniques of their cultivation as well as methods of delivery for their efficiency (Brown et al. 1997, Muller-Feugaet al., 2003).*Nannochloropsis, Skeletonema costatum, Navicula, Nitzschia, Chlorella spp., Dunaliella spp*. are some major microalgal species used in aquaculture (Shields and Lupatsch, 2012; Nagappan, 2021).Application of algal as feed for animals has been correlated to development of overall healthy animal physiology by lowering cholesterol, boosting immunity, improving gut functioning, increasing quality milk production as well as meat and egg quality (Liu et al., 2013; Suresh et al., 2017; Costa et al., 2022).

   Dunaliella salina, Nannochloropsis granulate, Tetraselmischui, Phaeodactulum, Scenedesmus and Chlorella are some commonly used feeds for livestocks (Shields andLupatsch, 2012; Saadaoui, 2021; Costa et al., 2022).

Table 1: Algal species with their potent role in emerging areas of bios prospects

Name of the species	Algal group	Uses	References
Acutodesmus dimorphus	Green alga	Biofertilizer	Gonzalez and Sommerfeld (2016)
Anabaena oryzae	Cyanobacteria	HM (Cu, Zn) removal	El-Bestawy (2008)
Anabaena sp.	Cyanobacteria	Biofertilizer	Chittoraet al. (2020)
Anabaena spiroides	Cyanobacteria	Plastic degradation	Kumar et al. (2017)
Anabaena variabilis	Cyanobacteria	HM (Cd) removal	El-Hameed et al.(2021)
Aphanizomenonflos- aquae	Cyanobacteria	Food	Kay and Barton, (2009)
Arthrospiraplatensis	Cyanobacteria	Food	Kejzar (2021); Aljobair (2021)
Arthrospira sp.	Cyanobacteria	Bioplastic production	Arora et al. (2023)
Aulosira fertilissima	Cyanobacteria	HM (Cd, Pb, Cu, Zn, Ni) removal	Singh et al. (2007)
Calothrix marchica	Cyanobacteria	HM (Cd, Hg, Pb) removal	Inthornet al. (2002)
Chlamydomonas reinhardtii	Green alga	HM (Co, Cd) removal	Macfie and welbourn (2000)
Chlorella vulgaris	Green alga	HM (Ni) removal	Mehta and Gaur (2001)
Chlorella vulgaris	Green alga	Plastic degradation	Falah et al. (1964)
Chlorella vulgaris	Green alga	Biofertilizer	Dineshkumaret al. (2017)
Chlorella pyrenoidosa	Green alga	Biofuel production	Das et al. (2018)
Chlorella pyrenoidosa	Green alga	Bioplastic production	Das et al. (2018)

Chlorella sp.	Green alga	Food	Spolaoreet al. (2006), Kay and Barton, (2009)
Chlorella vulgaris	Green alga	Bioplastic production	Selvaraj et al. (2021)
Chlorococcum humicola	Green alga	Antimicrobial activity	Bhagavathyet al. (2011)
Chlorococcum sp.	Green alga	Biofertilizer	Deepika and MubarakAli, (2020)
Dolichospermum crassum	Cyanobacteria	Anticancer activity against prostrate and colon cancer	Senousyet al. (2020)
Dolichospermum spiroides	Cyanobacteria	Anticancer activity against hepatic cancer	Senousyet al. (2020)
Dunaliella sp.	Green alga	Food	Spolaoreet al. (2006)
Hapalosiphon hibernicus	Cyanobacteria	HM (Cd, Hg, Pb) removal	Inthornet al. (2002)
Mastagocladus sp.	Cyanobacteria	HM (Cd, Hg, Pb) removal	Inthornet al. (2002)
Microcystis aeruginosa MKR 0105	Cyanobacteria	Biofertilizer	Grzesiket al. (2017)
Nannochloropsi ssp.	Green alga	Biofuel	Wang and wang, (2012)
Nostoc carneum	Cyanobacteria	Plastic degradation	Sarmah and Rout, (2019)
Nostoc linckia	Cyanobacteria	HM (Cr,Cu,Fe,Ni,Zn) removal	Cepoiet al. (2021)
Nostoc muscorum	Cyanobacteria	Bioplastic production	Arora et al. (2023)
Nostocmuscorum .	Cyanobacteria	Anticancer activity	Shanabet al. (2012)
Nostoc sp.	Cyanobacteria	biofertilizer	Chittoraet al. (2020)
Oscillatoria sancta	Cyanobacteria	Anticancer activity against breast cancer	Senousyet al. (2020)
Oscillatoria sp.	Cyanobacteria	Anticancer activity	Shanabet al. (2012)

Scenedesmus dimorphus	Green alga	Plastic degradation	Kumar et al. (2017)
Scenedesmus obliquus	Green alga	HM (Cd) removal	Monteiro et al. (2009)
Scenedesmus obliquus	Green alga	Food	Hlaing (2020)
Scenedesmus sp.	Green alga	Food	Kay and Barton, (2009)
Schizochytrium sp.	Green alga	Biofuel	Wang and wang, 2012
Spirulina platensis	Cyanobacteria	Food	Marzieh Hosseini et al. (2013)
Spirulina platensis	Cyanobacteria	HM (Co, Cu, Zn) removal	Vannela and verma, (2006)
Spirulina platensis	Cyanobacteria	Biofertilizer	Dineshkumaret al. (2017)
Synecchococcus sp.	Cyanobacteria	HM (Pb, Cd, Cr, Ni) removal	Gardea-Torresdeyet al. (1998)
Synechococcus sp. MA19.	Cyanobacteria	Bioplastic production	Arora et al. (2023)
Synechocystis PCC6803	Cyanobacteria	Bioplastic production	Arora et al. (2023)
Tolypothrix tenuis	Cyanobacteria	HM (Cd, Hg, Pb) removal	Inthornet al. (2002)
Westiellopsis prolifica	Cyanobacteria	Biofertilizer	Dutta and Baruah (2020)

IV. RESEARCH TREND AND FUTURISTIC APPROACH

Bibliometric analysis is the common and thorough method for studying and analysing vast amounts of scientific data (Donthuet al., 2021).It allows for the enhancement of research ideas and trends in particular topics for greater knowledge. Bibliometric analysis of "Microalgae" research using the data collected on 11th August 2023 from Scopus database revealed a total of 23,904 research articles were visualized through documented forms which are limited to only "Article", "Microalgae', "Microalga", "Algae" and "Microorganisms". Interestingly, the analysis of keywords shows that the most frequently used keywords in this aspects are "Microalgae/Microalga" and "Microorganisms" followed by "Chlorella", "Phospholipids", "Lipids", "Metabolism", "Bio products" and "Aerobic treatment". The graphical representation in Figure 2 is the keywords cluster arranged in network form for better visualization. The information gathered through this network revealed that among the 23,904 documents of microalga, Chlorella vulgaris is the most explored species which could have the highest prospects toward lipid extraction and aerobic treatment process. Thus, we could understand that Chlorella vulgaris could be a better agent in all aspects.

On the other stance Figure, 3 data showed that "Department of food science and Biotechnology, Gachon University", "Department of health science and Technology, Gachon advanced institute for health sciences and Technology", "Department of Microbiology, College of Medicine, Gachon University", Department of molecular medicine, College of Medicine, Gachon University", "Division of life science, Korea polar research institute, South Korea" and "Lee gilya cancer and diabetes institute, Gachon University" are the organization related to Co-authorship of research in the field of microalgae. The information could indicate that there are many scopes in microalgae research in the aspects that are not dealt with for other microalgae members.

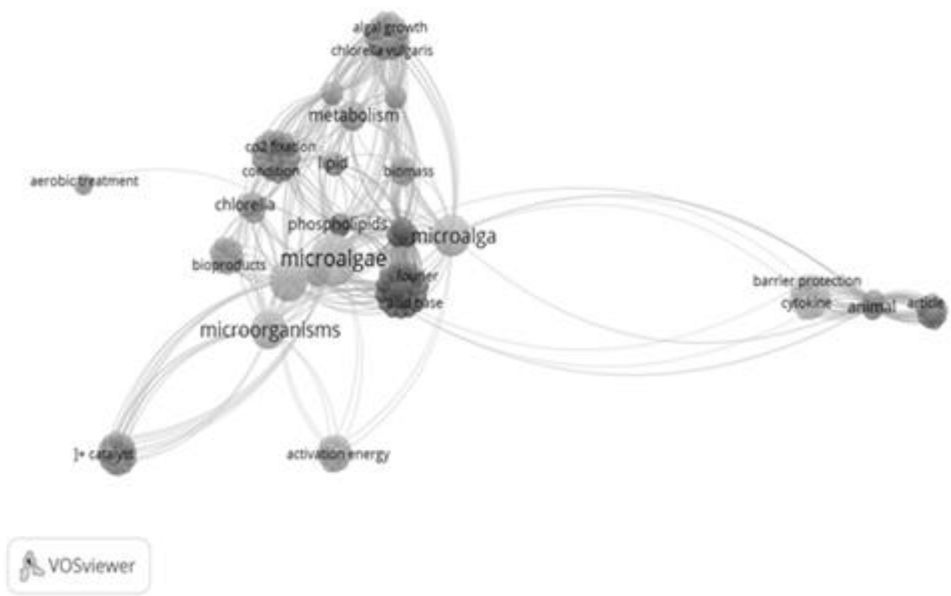

Figure 2: Network Analysis of Keywords

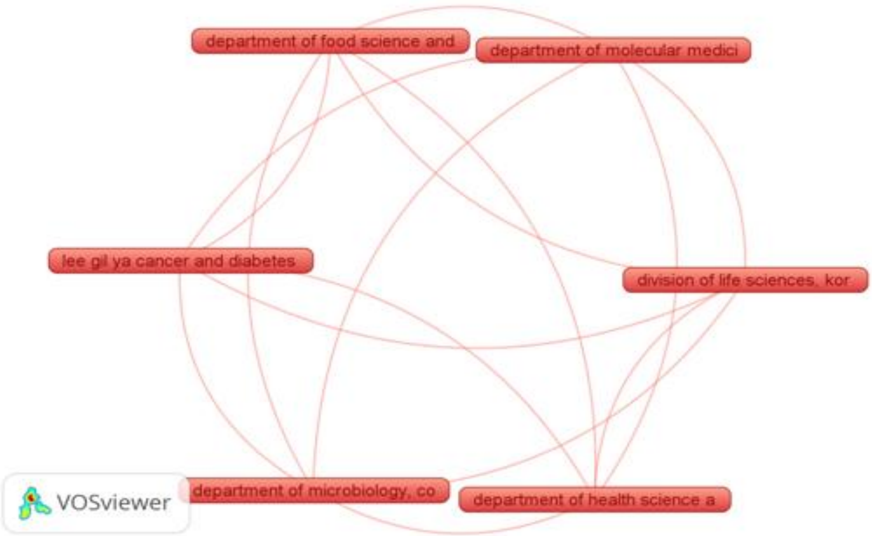

Figure 3: Network analysis of co authorship of organizations in microalgae

V. CONCLUSION

Even while microalgae exhibit enormous promising features, there are still issues to be solved, including identification of a greater number of potential species for industrial uses, improving cultivation methods to produce higher amount of biomass and ensuring economic sustainability. Inspite of these, continued research and technological development are steadily enhancing microalgae's bio prospects and broadening their range of industrial use which in turn will lead to a better and sustainable future.

Author Contributions

NK: Investigation, visualization, software, writing-original draft, editing; SN: Visualization, writing-original draft; TC: Writing-original draft, editing; BB: Writing-original draft; PPB: Supervision, investigation, visualization, writing- reviewing& editing.

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