Sustainability in anticancer drugs development

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Abstract. Cancer remains one of the most fatal disease threats to mankind. As the development of healthcare and medical science it is important to come up with a sustainable solution to deal with cancer treatment. Despite the fact that many of the approved drugs still exhibit high systemic toxicity, primarily as a result of their lack of tumor selectivity and current pharmacokinetic drawbacks (such as low water solubility), which adversely affect drug circulation time and bioavailability, anticancer research has produced impressive results in recent decades. The sensitivity of anticancer medications to various parameters has been proven by stability tests, which were conducted under gentle settings during their formation or during stressful exposure to high temperature, hydrolytic media, or light source. Because of this, the development of degradation products is evaluated in pharmaceutical formulations as well as in hospital waste released into the environment. Many formulations have been created to date with the goals of enhancing medication stability, lowering hazardous side effects, and attaining tissue-specific drug targeting. In targeted cancer therapy, the creation of prodrugs offers a viable approach to enhancing the stability, effectiveness, and selectivity of active ingredients. According to recent research, anticancer medications can be made more soluble, stable, and pharmacokinetic by incorporating them into vesicular systems like polymeric micelles or cyclodextrins or by using nanocarriers containing chemotherapeutics that bind to monoclonal antibodies. In this work, we provide an overview of the most recent developments in our understanding of the creation of potent, very stable anticancer medications that are either encapsulated in nanosystems or designed as stable prodrugs.

Keywords: Anticancer drugs, economic sustainability, environmental impact, Drug resistance.

1 Introduction

Cancer is a complex disease which is caused by the cancerous cells constantly dividing and spreading throughout the body . It is also recognized as a group of diseases which have their own changed behaviors and dynamics . Cancer can affect virtually any part of the body, including the lungs, breast, prostate, colon, skin, and many others. This is a criteria of medical science and innovation where sustainability, social development, feasibility for all kinds of status plays a crucial role to provide a future with the risk of cancer. To provide more

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effective treatment, the development of anticancer drugs comes to the forefront [1].This review paper focuses on the development of anticancer drugs, their characteristics and how they are getting more and more potential in cancer treatment. As cancer is a group of diseases that is uncontrolled by the tumeric growth of the cancer cells [2]. Anticancer drugs have historically played a significant role throughout history among various cancer treatment methods[3].

Cancer has given great threat to human health, its impact is not only limited to individuals but also their society and family members. Depending on the cancer stages that is set by the medical science it can be life threatening at a certain stage [4]. Even when not fatal, it can cause significant pain, discomfort, distress and misery to the one who is affected [5]. Also it can be distress to the family and closed ones of the patients. Not only physically but emotionally also cancer may cause various impacts [6]. It brings fear, anxiety, stress, hopelessness about life among the individuals. It can be a devastating experience fighting a cancer journey for the patient itself and their loved ones. Also the economic and financial impact through all those cancer treatments like chemotherapy, radiotherapy and also so many daily doses of heavy drugs and medicines is also painful [7]. That can also lead to financial burden and loss in productivity among the families [8].

The above reasons are enough causes to come up with a better cancer treatment therapy which reduces all this kind of distressesAs a result, anticancer drug development has prompted academics, pharmaceutical companies and doctors and medication experts for advancements of the medicines. It is crucial to understand the weight of this crisis for developing effective strategies and treatment for the better future [9].

2 Types of anticancer drugs:

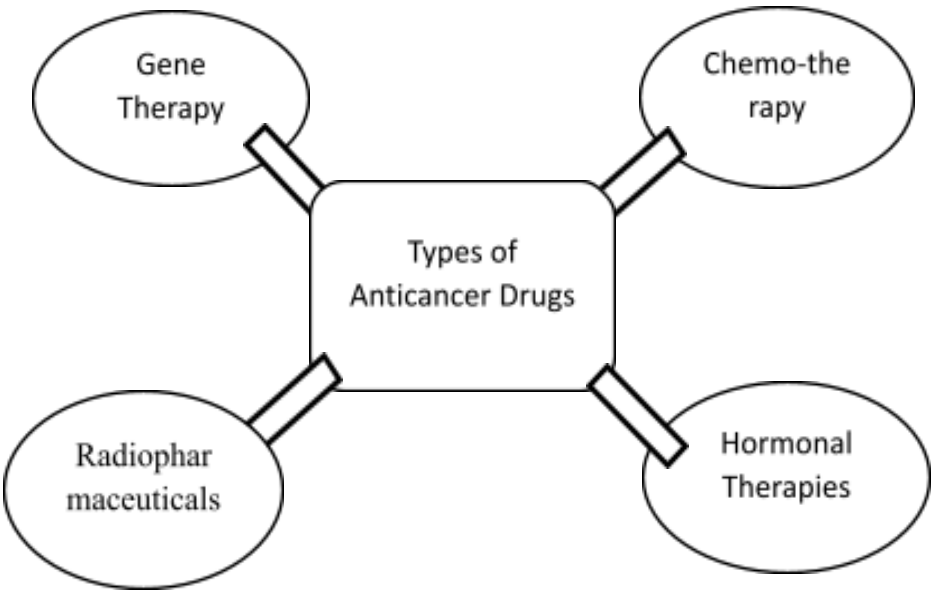

Fig. 1. Types of anticancer drugs

3 Various characteristics of anticancer drugs:

Table 1. This table contains different characteristics and the properties of a typical anticancer drug which to keep in mind while developing one and how it is used in various cancer treatments.

Aspect	Chemotherapy	Hormonal Therapies	Radiopharmaceuticals	Gene Therapy	References
Mechanism of Action	Cell cycle disruption, DNA damage, apoptosis	Hormone receptor inhibition, apoptosis	Targeted radiation therapy, DNA damage	Gene modification, immune activation	[11]
Selectivity	Non-specific, affects rapidly dividing cells	Selective for hormone-sensitive cancers	Selective targeting of cancer cells	Specific gene or cell type targeting	[12]
Main Indications	Various cancer types, both solid tumors and hematologic malignancies	Hormone receptor-positive breast and prostate cancers	Thyroid cancer, neuroendocrine tumors	Multiple cancer types, especially those with genetic mutations	[13]
Common Drugs/Agents	Paclitaxel, cisplatin, doxorubicin	Tamoxifen, aromatase inhibitors, LHRH agonists	Iodine-131, lutetium-177	Oncolytic viruses, CRISPR-Cas9	[14]
Side Effect	Nausea, bone marrow , hair loss suppression	Menopausal symptoms, bone density loss	Radiation-related side effects, potential radiation toxicity	Immune-related adverse events, off-target effects	[15]
Clinical Trials	Extensive use and clinical trials over decades	Ongoing research in optimizing	Clinical trials to refine dosing and delivery	Active trials to assess safety and efficacy	[16]

4 Mechanisms of Action: -

As the main cause of cancer is multiplication and spreading of cancer cells and uncontrolled growth of them, anticancer drugs use various mechanisms to stop that. These mechanisms are specially made to control the abnormality of cancer cells. Here are listed some common mechanisms for them:

4.1 Cell Cycle Inhibition:

It is a very important action that is used by anticancer drugs to abrupt the growth of the cancer cells. It is a modulating process that controls cell birth through division into two daughter cells. This cycle contains various phases like, G1(gap 1)S (synthesis phase), M (mitosis) phases ,G2 (gap2), with the checkpoints in between to certify proper DNA replication, repair [18].

This is how the cell cycle inhibition works:

4.1.1 G1 Phase Inhibition:

It arrests cancer cells in G. In this phase theses drugs block the progression beyond G1 and stops it from entering to S phase. By this it inhibits DNA replication and halts the growth of the cancer cell. DNA synthesis also gets forbidden by the drugs beyond this phase. Example of such drugs is CDK (cycline dependent kinase).

4.1.2 S Phase :

After G1 phase if the cell enters into the S phase there takes place DNA replication. The anticancer dugs inhibits the proper replication of the cell and such duplication lead to to killing of the cell and sometimes also forming an unstable genome. Drugs like hydroxyurea can inhibit DNA synthesis during the synthesis (S) phase.

4.1.3 Mitotic Inhibition:

Some anticancer drugs target the M phase that is mitosis phase of cell cycle, where cells divide into two daughter cells. These drugs disrupt the mitotic spindle, that is essential for proper chromosome separation during cell division. As a consequence, cancerous cells cannot complete mitosis, leading to cell death [19]. Paclitaxel and vinblastine are examples of drugs that act during mitosis.

4.1.4 Checkpoint Inhibition:

Checkpoints are control points in the cell cycle that ensure the integrity of DNA before progression to the next phase. Inhibiting checkpoint proteins like checkpoint kinase (Chk) can lead to cell cycle arrest, preventing damaged cells from continuing to divide. Some targeted therapies and chemotherapy drugs interfere with checkpoint proteins.

Cell cycle inhibition is a powerful strategy to target swiftly dividing cancerous cells. However, it can also affect normal,non-cancerous healthy cells with high proliferative rates, such as those in the bone marrow and gastrointestinal tract, leading to side effects commonly associated with chemotherapy [20]. The development of more selective and targeted anticancer drugs aims to minimize these side effects while maximizing the therapeutic effect on cancer cells.

4.2 Apoptosis Induction:

Apoptosis, referred to as organized cell death, is a highly modulated and orderly process by which cells in multicellular organisms undergo self-destruction. This process is very essential for maintaining tissue homeostasis and eradicating damaged or infected cells, and shaping development and growth of the tissues and organs. Apoptosis induction involves a series of molecular events that can lead to the cell death without causing inflammation, harm to neighbouring cells [21]. Here's an explanation of how apoptosis is induced:

4.2.1 Initiation of Apoptosis:

Apoptosis is triggered by numerous internal and external signals. These type of signals can originate from factors within the cell (intrinsic pathway) or external influences (extrinsic pathway).

- *Intrinsic Pathway:*

Internal factors such as DNA damage, cellular stress, or the presence of abnormal proteins can initiate apoptosis. These signals activate proteins like p53, which mostly acts as a "guardian of the genome" and also plays a pivotal part in monitoring DNA integrity. In response to DNA damage, p53 can activate pro-apoptotic genes and suppress anti-apoptotic genes, setting the stage for apoptosis [22].

- *Extrinsic Pathway:*

External signals, often involving interactions with neighboring cells or molecules, can also trigger apoptosis. This pathway typically involves cell surface receptors known as death receptors, such as Fas and TNF receptors. When these receptors are engaged by their respective ligands (Fas ligand or tumor necrosis factor), they transmit signals that initiate the apoptotic cascade.

4.2.2 Activation of Caspases:

Once apoptosis is initiated, a family of protease enzymes called caspases become activated. Caspases have a central job in orchestrating the orderly dismantling of cells. They exist in an inactive form and must be cleaved and activated to carry out their functions.

- *Initiator:*

Initiator caspases, like caspase-8,caspase-9, are the first to become activated in response to apoptosis signals. They trigger a cascade of events which guides the activation of effector caspases.

- *Effector :*

Effector caspases, like caspase-3 ,caspase-7, are accountable for executing the cellular changes associated with apoptosis. They cleave key cellular proteins, resulting in the characteristic morphological and biochemical changes of apoptotic cells [23].

4.2.3 Execution of Apoptosis:

As caspases become active, they initiate a series of events that lead to the hallmark features of apoptosis:

- *Cell Shrinkage:*

  Apoptotic cells undergo cytoplasmic and nuclear condensation, resulting in cell shrinkage.

- *Membrane Blebbing:*

  The cell membrane forms characteristic blebs or bulges.

- *Chromatin Condensation:*

  The DNA within the nucleus condenses and fragments.

- *Formation of Apoptotic Bodies:*

  The cell breaks into smaller membrane-bound fragments called apoptotic bodies.

4.2.4 Engulfment and Removal:

Once a cell has undergone apoptosis, it releases signals that attract phagocytes (e.g., macrophages) to consume and also digest the apoptotic bodies. This avert the release of potentially harmful cellular contents and ensures the safe removal of the dying cell without causing inflammation or damage to surrounding tissues.

Apoptosis induction is a finely tuned process essential for maintaining tissue health and preventing the survival of damaged or unwanted cells, including those with genetic mutations or infection. Dysregulation of apoptosis can contribute to various diseases, including cancer (where cells evade apoptosis) and neurodegenerative disorders (where excessive apoptosis occurs) [24]. Therefore, understanding and manipulating apoptosis is of significant interest in medical research and therapy development.

5 Some other types of mechanism of action: -

Aspect	Angiogenesis Inhibition	DNA Repair Inhibition	Immune System Modulation	references
Mechanism of Action	Inhibition of new blood vessel formation (angiogenesis) by targeting VEGF or its receptors	Interference with DNA repair mechanisms, often exploiting cancer cell deficiencies (e.g., PARP inhibition)	Activation or modulation of the immune system to identify and encounter cancer cells	[25]
Challenges	Development of resistance to anti-angiogenic agents, limited efficacy in some cancers, potential for toxicity	Identification of biomarkers predicting sensitivity to DNA repair inhibitors, resistance mechanisms, off-target effects	Immune-related adverse events, variability in patient response, overcoming immune evasion by cancer cells	[26]
Applications	Treatment of cancers that rely on angiogenesis for growth (e.g., colorectal, renal cell carcinoma)	Particularly effective in cancers with deficiencies in DNA repair (e.g., BRCA-Mutated tumours)	Broad applications across multiple types, including melanoma, lungs, and bladder cancer also	[27]

6 Green chemistry principle in anticancer drug development

6.1 Introduction to green chemistry

With benefits over conventional organic synthetic methods, green chemistry is a contemporary method for the synthesis of organic chemicals and tailored pharmaceuticals

under simple protocols, efficient settings, ecologically benign, and high yielding way to molecules. It typically lowers expenses, waste byproducts, and creates ecologically favorable practices[28].This chemistry covers a range of contemporary methods for creating bioactive compounds, including sonochemical synthesis with ionic liquids, solid phase supported free of solvents synthesis, interaction with organocatalyst, and microwave-assisted synthesis. Additionally, pharmaceutical businesses are refining their substances to minimize ecological concerns and to lessen environmental hazards.

6.2 Solvent-free synthesis

In the field of developing anticancer drugs, solvent-free synthesis is a shining example of sustainability, providing an important change towards more ecologically friendly and ecologically conscientious approaches. This method reduces energy consumption and trash production by doing away with the requirement for solvents, which lessens the environmental impact of medication synthesis processes[29]. Also solvent free synthesis is a part of sustainability and green chemistry as it reduces danger to human health using harmless chemicals. That is why it is used in production of anticancer drugs for it's effectiveness, for not only revolutionizing the treatment in cancer thrapy but alsoo to the more general sustainability objectives of the pharmaceutical industry.

6.3 Catalysis

Catalysts generally cut down the activation energy for a reaction and help the chemical reaction to take place even with limited resources. That is why it play a crucial role in developing anticancer drugs in a sustainable way. It has advantaes in the case of conserving energy, waste management and efficiency. The main role of catalysts in developing anticancer drugs is it activates particular chemical bonds which clears the reaction path and increases the final good. This takes less raw material and generates less amount of byproducts and wastes in comparison to the normal. Moreover catalytic reactions take place into mild environments needing lower energy amd improving the whole process[30]. This helps to reach sustainable development of cancer drugs.

6.4 Case Studies of Green Chemistry in Anticancer drug discovery:

Several case studies show how green chemistry principles can be successfully used to the search for anticancer treatments, proving the practicality and efficacy of sustainable methods. One well-known example is the synthesis of artemisinin derivatives, which are typically used as antimalarial drugs, employing environmentally benign methods like solvent-free synthesis or biocatalysis. Green chemistry presents an opportunity to reuse pre-existing compounds for oncological applications, as these derivatives with their improved pharmacokinetic properties and encouraging anticancer activity demonstrate. Furthermore, platinum-free anticancer drugs have emerged as an alternative to platinum-based drugs like cisplatin by utilising organometallic combinations and metal-free compounds synthesised with eco-friendly techniques. These materials work just as well while lessening the harm that platinum mining and synthesis do to the environment. Additionally, taxol equivalents have been produced by the use of green chemistry in natural product-inspired synthesis.

6.4.1 Artemisinin Derivatives:

The sweet wormwood plant is the source of artemisinin, a potent antimalarial chemical. To produce artemisinin derivatives with enhanced anticancer activity, green synthesis techniques have been investigated by researchers.Using solvent-free synthesis and biocatalysis, scientists have produced new molecules with improved pharmacokinetic properties and less environmental impact.

6.4.2 Platinum free anticancer drugs:

Although platinum-based medications like cisplatin are frequently used as cancer chemotherapy, their toxicity or resource-intensive manufacture present environmental problems. Green chemistry techniques have produced metal-free molecules and organometallic complexes as platinum substitutes. These substances reduce the environmental impact of platinum mining or synthesis while displaying anticancer activity that is on par with or better than existing chemicals.

6.4.3 Natural Product inspired synthesis:

Drug researchers have long drawn inspiration from natural compounds, yet the techniques involved in their extraction or isolation can have negative environmental effects.Anticancer molecules inspired by natural products have been synthesised by the use of green chemistry principles, resulting in sustainable processes. For instance, the production of taxol analogues using renewable feedstocks and catalytic synthesis techniques has produced molecules with strong anticancer activity and decreased the need for extraction processes that are detrimental to the environment.

6.4.4 Bioactive Peptides:

Due to their selectivity and low toxicity, peptides have great potential as anticancer medicines; nevertheless, conventional peptide synthesis procedures require solvents and dangerous reagents. To expedite peptide synthesis while reducing environmental effect, green chemistry techniques like solid-phase synthesis and microwave-assisted peptide synthesis have been used.These techniques facilitate the effective synthesis of biologically active peptides for treatment of cancer by minimising waste formation and optimising reaction conditions.

7 Sustainable Sourcing of Natural Products :

7.1 Natural products significance in Anticancer drugs:

Natural products have a significant role in the search for anticancer drugs because of their various and rich chemistry, which have developed through millions of years through natural selection. Natural products obtained from microorganisms, plants, and marine life have long been a rich source of lead chemicals for the synthesis of pharmaceuticals, including anticancer medicines. These substances frequently have distinct bioactive characteristics and intricate molecular scaffolds, which make them excellent candidates for focusing on particular molecular pathways that contribute to the development of cancer. In addition, a large chemical variety reservoir found in natural products can be tapped into by screening and optimising procedures to find new therapeutic candidates with improved potency or

selectivity.

7.2 Challenges in Unsustainable Sourcing:

In the process of developing anticancer medications, non-sustainable sourcing raises a number of intricate ethical, social, and environmental concerns. Unsustainable sourcing practises have the potential to seriously harm the ecosystem and reduce biodiversity. Overharvesting medicinal plants and arbitrarily taking natural resources from fragile ecosystems are two examples. Not only does this habitat loss threaten animal and plant species, but it also puts populations of medicinal plants in danger of going extinct, which could complicate current efforts to find new medications. Additionally, unethical sourcing can have detrimental social and economic repercussions, particularly in areas where natural resource-dependent communities depend on their livelihoods. Overuse of medicinal herbs can exacerbate poverty, disrupt traditional knowledge networks, and increase social unrest around resource distribution and access.

8 Economic Sustainability and obstacles in Anticancer drug development:

One of the major obstacles that comes in the way of developing sustainable anticancer drugs is lack of advancement and, not enough medical resources and high cost and long term commitment to research. As it is still under development it can take time to examine new characteristics and then perform and test it on a patient and come up with a long term solution, which leads to high expenses in the field of research and development (R&D). It is still in a vulnerable state where there are high failure rates in the process. Furthermore developing the solution by the means of maintaining all the safety regulations and all the regulatory requirements adds up to the cost even more. These key economic points restrict access to medicines that could save thousands of lives.

8.1 Economic challenges in healthcare:

While developing any kind of product it requires significant research and development and economic support. But the process becomes harder with less accessibility, high cost and hindered innovation. The development costs are boosting day by day as there is a significantly lengthy timeline and high failure rate in recently invented methods. Furthermore the initial testaments have to go through various severely taxing processes, clinical trials and approvals. Which keeps the timeline more and more. The monetary burden also takes place while availing the product to the normal people which makes it more difficult for them to avail these treatments. After all of this, the process from the beginning, researching about their drug, coming up with a solution and after developing a solution availing it to normal people in a reasonable and sustainable way is an economic challenge.

8.2 Pricing Strategies for anticancer drugs:

To verify an anticancer medication and carefully analyze all the aspects between creativity, affordability and fair access to healthcare is contingent upon pricing methods and patient access. Anticancer drugs are quite expensive because they are new to the market, still under development and their development process is quite high. Moreover, initiatives like patent pooling, mandatory licensing, and the manufacturing of generic drugs might help increase access to competitively priced anticancer drugs, particularly in low- and middle-income

nations where the prevalence of cancer is typically highest. In sustainable development our goal is to provide life-saving therapies to all of them who are in need, despite the cost. So contributing anticancer drugs to sustainability is still a big challenge. We can keep on trying so by prioritizing patient access and cost during the anticancer medication discovery process, and by offering incentives for creativity and research expenditure.

9 Recent Advances in Anticancer Drug Development:

9.1 Precision Medicine and Personalized Therapies:

Precision medicine brings out a special molecular characteristic of every patient's cancer which is bringing out new versions of cancer therapy treatment [28]. Recent advancements in precision medicine have significantly improved patient outcomes and set the stage for the development of personalized therapies.

9.1.1 Genomic Profiling:

- *Next-Generation Sequencing (NGS):*

The advent of NGS technologies has revolutionized the genomic characterization of cancer. These high-throughput techniques allow for the comprehensive analysis of the entire cancer genome, identifying driver mutations, copy number alterations, and fusion genes. The example of the this can be EGFR inhibitors like osimertinib which helps and spots the mutations of non-small cell lung cancer (NSCLC), it has shown an outgrown result among patients conditions [29].

- *Comprehensive Tumor mutating:*

This approach uses NGS inside like other exome sequencing and RNA sequencing to identify places where we can perform mutations and other targeted therapies based on the molecular test result of the patient's tumour.

9.1.2 Liquid Biopsies:

- *Circulating Tumor DNA (ctDNA) binding:*

It is a part of liquid DNA biopsy. It offers a non-intrusive and real time monitoring of cancer treatment. It helps to detect any kind of mutations or genetic alteration in the stem cells and in the bloodstream to provide more information for decision making. For example this process helps to identify emerging resistance mutations to targeted bodies and helps to provide modification in between medication periods [30].

- *Early Detection of cancer :*

With the help of liquid biopsies we can detect cancer at an early stage. As it includes real time monitoring of the stem cells we can identify every change or mutation that is occurring in the cells.

9.1.3 Targeted Therapies:

- *Tailored Drug Selection in targeted therapies :* This method includes precision

medicine, which is becoming a molecular driving force for cancer. With real time monitoring and based on the specific genetic alterations of the cancer cells in a patient's body we select the drugs for therapy. For example, HER2-positive helps in breast cancer which follows this technique [31].

- *Resistance Mitigation technique:* Targeted therapies help us to keep an eye on the secondary mutation pathways of cancer cells. As these resistance mechanisms appear at the treatment time, precision medicine enables the selection for alternative medication therapies to overcome resistance.

9.2 Nanotechnology in Drug Delivery:

Integrating nanotechnology in the field of drug delivery is offering more innovative solutions to increase the effectiveness, precision and safety in the anticancer treatment. This field focuses on building nanoscale drugs or nanoparticles which can transport the therapeutic agents created to the tumor sites with less resistance and unparalleled precision [32].

9.2.1 Nanoparticle-Based Therapies:

- *Using Liposomal Formulations:*

Because liposomes are highly biocompatible, biodegradable, and immunogenicity-free, they are now thought to be the most widely employed nanocarriers for a variety of hydrophobic and hydrophilic compounds that have the potential to be active. Moreover, liposomes have demonstrated improved drug solubility, regulated dispersion, and surface modification ability for focused, extended, and sustained release. Liposomal formulation such as (Doxli) is proven to be a method of various cancers including breast cancer [33].

- *Polymeric Nanoparticles:*

It offers a versatile drug delivery because polymeric nanoparticles are constructed from bio polymars. These nanoparticles use cargo in response to to specify stimuli, like pH changes or enzyme activity in the microenvironment. Thus reduces the off - target effect of drugs on the tumor site and enhances the productivity of the drug at the activation site.

9.2.2 Targeted Nanocarriers:

- *Active Targeting by Nanocarriers:*

Nanoparticles can be designed to target some selective molecular markers on cancer cells. This kind of active targeting strategy ensures more efficiency, less resistance and increases drug delivery spot efficiency to cure the damaged cells. A significant example of this can be HER-2 targeting antibodies which has shown great results in only finding HER-2 positive breast cancer cells among the targeted site[34].

- *Passive Targeting or EPR Effect:*

It is also called enhanced permeability retention (EPR) effect. It appears because of the dripping vascular and lymphatic damage of the tumor. Nanoparticles can leverage the EPR effect by accumulating tumors. allowing passive targeting of drug delivery to cancer sites.

9.2.3 Advantages:

- *Minimized Systemic Toxicity and side effects:*

Nanoparticles eliminate a lot of side effects such as chemotherapy does to a patient. By delivering the drugs directly to the tumors it reduces the exposure to healthy tissues and alleviates adverse effects. They minimize the systemic toxicity associated with many anticancer drugs.

- *Improved Pharmacokinetics in bloodstem:*

Nanoparticle drugs extend the circulation time of drugs which leads to lengthen the exposure of the drug in the bloodstream. This reduces frequent dose taking and enhance drug potency.

9.3 Combination Therapies in Cancer Treatment:

Combination therapy is justified by the use of medications with distinct modes of action, which reduces the possibility of the development of resistant cancer cells. Combining medications with distinct effects allows each medication to be taken at the recommended dosage without experiencing unbearable side effects. By combining different therputic approach like chemotherapy, radiation, immunotherapy, targeted therap, oncologists can add various aspects in tumor biology, discover advanced medical technology and evade resistances in treatment [35]. This sophisticated approach increases the likelihood of tumor regression but also minimizes the risk of regularity.

A key component of cancer therapy is the combination of two or more therapeutic interventions to precisely target pathways that support or cause cancer . The combination therapy technique is typically considered more effective than the monotherapy approach, despite the fact that monotherapy is still a highly common treatment option for many different kinds of cancer. Traditional monotherapy methods non-selectively attack cells that are actively multiplying, which eventually results in the death of both malignant and healthy cells.

9.4 Immunotherapy Breakthroughs in Cancer Treatment:

Cancer still has a high death rate and is one of the main obstacles to increasing total human survival despite all the research done to combat it. Many treatments, including surgery, radiation, chemotherapy, hormone therapy, targeted therapy, stem cell therapy, and immune therapy, were tried for decades to cure cancer. Among these, immunotherapy considerably outperformed the prior standard of care in terms of cancer patient survival and quality of life. Genomic instability causes mutations in tumor antigens, which are characteristic of cancer. Like that CAR-T therapy prevents hematologic malignancies. This revolutionary therapy has yielded remarkable response rate in patients with obstinate forms of leukemia and lymphoma [36].
Here are some notable immunotherapy breakthroughs:

9.4.1 Immune Checkpoint Inhibitors:

checkpoint inhibitors of immune, like as pembrolizumab (Keytruda), ipilimumab (Yervoy), nivolumab (Opdivo), have revolutionized cancer therapy. Blocking proteins like CTLA-4, PD-1, Pembrolizumab, Ipilimumab can leverage to attack the immune system. These drugs have shown significant impact across multiple cancer types like melanoma and bladder

cancer [37]. The approval of these medicines is an important advancement to combat cancer.

9.4.2 CAR-T Cell Therapy Breakthroughs:

CAR-T therapy or Chimeric Antigen Receptor therapy is like a living drug that are made from collecting T cells from the cancer patient and then it is reengineered in the laboratory to produce protein layers on the surface of the T-cells called CAR protein. This therapy has shown most effectiveness on various blood cancers like leukemia, lymphoma. Drugs like Kymriah, Yescarta has already been FDA approved as potential curative treatment options.

9.4.3 Tumor-Infiltrating Lymphocytes in Brief (TILs):

TIL therapy includes separating the T cells from the tumor of patient, T and B cells, which make up lymphocytes, are continually scouring the body for cells that shouldn't be there, such as cancer. As tumors enlarge, lymphocytes enter the tumor after identifying these cells as aberrant. These are known as TILs, or tumor-infiltrating lymphocytes. This method is mainly used to treat metastatic melanoma or other solid tumors.

9.4.4 Personalized Cancer Vaccines:

Personalized cancer vaccines are typically planned to stimulate the immune system of a patient to target specific mutations or neoantigens present in their cancerous cells. This approach tailors treatment to each patient's special tumour profile. Several personalized cancer vaccine candidates are in clinical trials, offering potential breakthroughs in the treatment of certain cancer kinds [38].

10 Applications of the Anticancer Drugs: Key Points :-

Anticancer drugs are a cornerstone of cancer treatment, serving as powerful tools in the battle against malignant diseases. These drugs are designed to target and combat the uncontrolled growth and proliferation of cancer cells, ultimately aiming to reduce tumor size, alleviate symptoms, and improve patient survival. Their applications are multifaceted and encompass various stages of cancer management, including the following key points:

10.1 Primary Treatment:

Anticancer drugs are often employed as the primary treatment modality, particularly in cases where surgery or radiation therapy is not feasible. This primary treatment is known as chemotherapy and is commonly used for hematologic malignancies like leukemia and of solid tumors like as lung, breast cancer, cancer of ovary. Chemotherapy can also be administered as a only single agent or as a combination of various drugs to target different aspects of cancerous cell biology. By obstructing the cell cycle, inducing DNA damage, or blocking specific cellular pathways, chemotherapy aims to reduce tumor burden and control disease progression [39].

10.2 Adjuvant Therapy:

Anticancer drugs also find applications as adjuvant therapy, which is given after the primary treatment which is usually surgery to eliminate any existing cancerous cells and reduce the risk of reappearance. For instance, adjuvant chemotherapy is standard practice in breast

cancer treatment following tumour resection. By targeting residual cancerous cells that may have propagated beyond the site of primary tumour but are undetectable through imaging, adjuvant therapy aims to improve long-term survival outcomes [40].

10.3 Neoadjuvant Therapy:

Neoadjuvant therapy is the term for the practice of sometimes administering anticancer medications prior to surgery. This method is frequently used to reduce the size of large or locally advanced tumours, which makes surgical resection more practical and less intrusive. For instance, neoadjuvant chemotherapy is used to reduce the size of the tumour and raise the likelihood that breast-conserving surgery would be performed rather than a mastectomy [41].

10.4 Palliative Care:

Palliative care, which aims to improve the quality of life for patients with extremely advanced or metastatic disease, depends heavily on anticancer medications to relieve cancer-related symptoms. The goals of palliative chemotherapy are to reduce pain, manage side effects such nausea and exhaustion, and delay the growth of the tumour. Even in cases where a cure is not achievable, it can improve the comfort and general well-being of patients.

10.5 Targeted Therapy:

Advances in the study of cancer have given rise to a class of anticancer medications known as targeted therapies, which target certain molecules or pathways that are involved in the development and spread of tumours. In order to reduce side effects, these medications are made to be less hazardous and more selective towards healthy cells. Many cancer types can benefit from targeted therapy. For example, EGFR-mutant lung cancer can be treated with EGFR inhibitors like osimertinib, and HER2-positive breast cancer can be treated with trastuzumab.

10.6 Immunotherapy:

Cancer still has a high death rate and is one of the main obstacles to increasing total human survival despite all the research done to combat it. Many treatments, including surgery, radiation, chemotherapy, hormone therapy, targeted therapy, stem cell therapy, and immune therapy, were tried for decades to cure cancer. Among these, immunotherapy considerably outperformed the prior standard of care in terms of cancer patient survival and quality of life. Genomic instability causes mutations in tumor antigens, which are characteristic of cancer. Like that CAR-T therapy prevents hematologic malignancies.A handful of survival rates and results have been found in the recent dates in patients [42].

These key points highlight the diverse applications of anticancer drugs in the management of cancer, ranging from primary treatment to alleviating care. The ongoing research and development in these field of targeted therapy like immunotherapy expands more effective medication procedure as well as financial incentives for business to gather green energy.

11 Challenges and Future Directions

11.1 Policy Interventions of anticancer drugs for sustainability:

To promote sustainable development through anticancer drugs, we need proper research, development, management, ethical sourcing, proper business procedure and environmental objectives. The regulatory policies are persuaded by the global organizations, government who influence the support sustainability in the medical and pharmaceutical industry. The CSR (Corporate social responsibility) bodies encourage implementation of sustainable manufacturing methods and applying green chemistry principles in the synthesis of anticancer drugs manufacture. This include various regulation for reduction of negative environmental effects as well as financial incentives for business that follows green energy principals.

11.2 Emerging Technologies and trends to incorporate in R&D:

With the emerging technologies in bioengineering and healthcare industry are revolutionizing anticancer drug development. Advanced biotechnologies like CRISPR and various data driven algorithms help us to analyze past patient data and allows us to run test and scopes for development. AI-driven methods minimise the need for expensive research and animal testing by enabling researchers to more precisely identify new targets for therapy and optimize drug candidates by utilizing large datasets and computational models. Furthermore, new paths for carrying out more physiologically pertinent and forecasting preclinical studies are provided by biotechnology advancements like the creation of cell-based experiments, organ-on-a-chip technology, and three-dimensional bioprinting methods, which improve the effectiveness and dependability of drug screening.

11.3 Challenges in Advancing Sustainability Goals:

It is not easy to advance objectives for sustainability in anticancer drug development; there are many intricate roadblocks that call for coordinated efforts from stakeholders in many industries. The main challenge while manufacturing anticancer drugs is to minimize the barrier of profit and sustainability in the pharmaceutical sector. Distribution networks and local manufacture of drugs can be a solution of this problem as they come under green energy principals, but implementing them with a real business idea, training healthcare individuals and making them comfortable with the uprising technologies is a challenging task. Furthermore, the parliamentary environment makes it difficult to include sustainable principles on the ongoing regulatory management system as changing and reversing everything on a big scale can take a lot of time and resources.

11.4 Drug Resistance in Cancer Treatment:

One of the most complicated things to overcome in cancer treatment through anticancer drugs are the drug resistance. It occurs in a period of time when cells adapt the changes and become less reactive to the cancer cells and the killing rate decreases. The mechanisms in drug resistance include genetic mutation, DNA repair mechanism, tumor microenvironment, drug efflux etc. For these mechanisms various treatment methods are used from past few decades, like combination therapy, immunotherapy, adaptive therapy. But inspite of these advanced treatment methods it continues to hamper treatment efficacy.

In primary resistance cancer cells do not respond to the mentioned therapies . It can occur due to genetic variation, or because of the presence of drug-resistant subpopulations which were already present in the tumor cell. On the other hand acquired resistance occur due to selective pressure created during the treatment time [43].These days medical professionalists are using biomarkers to predict the resistance beforehand, and conducting various medical

trials to test new approaches.

11.5 Side Effects and Toxicity:

Anticancer drugs are a revolutionary approach for cancer treatment and medical science technology but it also comes with a handful of side effects and in some cases toxic reaction on the patient. These effects depend upon the drug type and it's characteristics and patient's individual body condition and adaptability. These side effects include nausea, anemia neutropenia, Mucositis, Thrombocytopenia reduce of blood cell counts etc,

It can also impose some long term damage on the body like, secondary cancers later in life due to the mutant effect. In some cases it may lead to organ failure or impairment. Like, Hepatotoxicity, kidney removal, pulmonary toxicity. Cardiotoxicity is another matter of concern with drugs associated like anthracyclines.

Minimising these side effects and toxic nature is under research and development. Professionals are trying to figure out the environment of a certain body type where these kind of effects may take place, and trying to come up with significant complimentary. Modern cancer care must include supportive care strategies such as anti-nausea drugs, growth hormones to increase blood cell formation, and focused interventions for certain side effects [44].

11.6 Access to Anticancer Drugs:

Equitable access to anticancer drugs is a critical aspect of cancer care that poses challenges globally. Disparities in access can be attributed to various factors, including economic disparities, healthcare infrastructure, and regulatory hurdles. High costs associated with some anticancer drugs, particularly targeted therapies and immunotherapies, create financial barriers for many patients. This economic burden extends to both patients and healthcare systems, often leading to difficult choices regarding treatment affordability.

In low-resource settings, limited healthcare infrastructure and lack of specialized cancer centres further exacerbate access challenges. Delays in diagnosis, inadequate treatment options, and a lack of trained healthcare professionals contribute to unfavourable outcomes for patients in these regions [45]

To address these disparities, international efforts are underway to increase access to essential anticancer medications. Initiatives include the development of affordable generic versions of key anticancer drugs, price negotiations with pharmaceutical companies, and support for low-income countries to strengthen their cancer care infrastructure. Furthermore, research into cost-effective treatment approaches and telemedicine solutions aims to extend the reach of cancer care to underserved populations.

11.7 Emerging Technologies:

With the emerging technologies in bioengineering and healthcare industry are revolutionizing anticancer drug development. Advanced biotechnologies like CRISPR and various data driven algorithms help us to analyze past patient data and allows us to run test and scopes for development. AI-driven methods minimise the need for expensive research and animal testing by enabling researchers to more precisely identify new targets for therapy and optimize drug candidates by utilizing large datasets and computational models. Furthermore, new paths for carrying out more physiologically pertinent and forecasting

preclinical studies are provided by biotechnology advancements like the creation of cell-based experiments, organ-on-a-chip technology, and three-dimensional bioprinting methods, which improve the effectiveness and dependability of drug screening.

Precision medicine, which is led by genomic profiling and molecular diagnostics, tailors cancer treatment to the unique genetic and molecular characteristics of each patient's tumor. With this method, targeted drug targets are identified and treatment response is predicted, resulting in more individualized and efficient medicines. Furthermore, advances in immunotherapy, such as immune checkpoint inhibitors and CAR-T cell therapies, use the immune system's ability to target cancer cells, and research is still being done to see how these treatments might be used to treat different kinds of cancer [46].

12 Conclusion

For an better environment and healthy future of mankind we need to ensure the integration of sustainability into all aspect of anticancer drug discovery. Considering all the tactics and technologies for the advancements in various ares of development by adopting green energy principals, waste management, environmental footprints and moral sourcing of natural resources. To achieve this goal we need economic as well as organizational support in managing the policies and passing laws for all the medical and pharmaceutical agencies to abide by for the sustainability goal. A lot of actions has been taken but there are still many more obstacles to deal with and therefore we need cooperation of every each individual.

Due to their ability to guarantee a controlled release of a sufficient amount of the drug at the intended site of action and to lessen the drug's sensitivity to physicochemical factors during the phases of preparation, management, and storage, anticancer agents included in nanosystems have now been shown to be therapeutically effective. Further benefits come from the ability to combine two or more medications in one vehicle since it lowers the dosage and, thus, the toxicity of each agent. Larger vesicles, like liposomes, are employed in these situations. Numerous investigations concentrating on the creation of novel formulations are still under progress.

12.1 Summary of Key Advances:

Personalised therapy and precision medicine have become important developments in the development of anticancer drugs. Liquid biopsies and genomic profiling have made it possible to identify certain molecular changes, which has guided the choice of targeted medicines according to the unique genetic profile of each patient. Better treatment outcomes, decreased toxicity, and increased drug delivery precision have all been made possible by the application of nanotechnology in drug delivery. Combination medicines have shown remarkably effective in boosting patient responses and overcoming resistance, one such example being the integration of immunotherapy with conventional treatments. Since the development of immune checkpoint inhibitors and CAR-T cell treatments, immunotherapy has been used to treat a wide range of malignancies with extraordinary effectiveness.

12.2 Future Prospects in Anticancer Drug Development:

Anticancer medication development has a bright and hopeful future. New technologies that will continue to influence the industry include organoids, 3D printing, and artificial intelligence. These technologies will speed up drug development, improve treatment planning, and make it possible to test drugs on tumour models that are unique to each patient.

Immunotherapy will become more applicable to a wider range of cancer types as a result of advancements in the field, and combination therapies will be refined to optimise therapeutic effectiveness while reducing resistance.

Furthermore, the discovery of novel targets, such as the tumour microenvironment, epigenetic modifiers, and cancer stem cells, may improve cutting-edge treatments. With treatments catered not just to genetic profiles but also to the unique molecular features of individual tumours, personalised, customised medicine will become more sophisticated. Nonetheless, issues including medication resistance, adverse effects, and fair access to innovative treatments. Overcoming these challenges will require collaborative efforts among researchers, healthcare providers, pharmaceutical companies, and policymakers.

In conclusion, the recent advances in anticancer drug development have brought us closer to a future where cancer treatment is more effective, precise, and patient-centered. While challenges remain, the collective pursuit of innovative therapies, combined with a deep understanding of cancer biology, continues to drive progress in the fight against cancer. As we look to the future, the hope is that these advancements will translate into enhancing survival rates, quality of life for the cancer patients, and ultimately, a world where this cancer is no longer an unconquerable adversary.

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