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Edible Vaccine: A Novel Approach to Immunization

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ABSTRACT

Edible vaccines represent an innovative and promising approach to immunization by utilizing genetically engineered plants to produce antigenic proteins capable of inducing immune responses when consumed. This novel strategy addresses many limitations of conventional vaccines, such as high production costs, the need for cold-chain storage, sterile injections, and trained medical personnel. In edible vaccines, genes encoding specific antigens from pathogenic organisms are introduced into edible plant tissues like banana, potato, tomato, rice, or maize. Upon ingestion, these antigens are released in the gut and stimulate both mucosal and systemic immunity, particularly enhancing secretory IgA responses, which play a crucial role in protecting against enteric pathogens. The development of edible vaccines offers significant advantages in terms of safety, ease of administration, and patient compliance, especially among children and populations with needle phobia. They also reduce the risk of contamination with human pathogens and eliminate biohazardous waste associated with syringes and needles. Edible vaccines hold promise for mass immunization programs in developing countries, where infrastructure and healthcare resources are limited. Additionally, they provide opportunities for low-cost, scalable production using agricultural practices. Despite their potential, several challenges remain, including dose standardization, stability of antigens during storage and digestion, regulatory approval, and public acceptance of genetically modified crops. Ongoing research focuses on improving expression levels, ensuring consistent immunogenicity, and addressing biosafety concerns. With continued advancements in plant biotechnology and regulatory frameworks, edible vaccines may become a viable alternative or complement to traditional vaccination strategies, contributing significantly to global disease prevention and public health.

Keywords: Edible vaccine, Pathogens, immunization.

INTRODUCTION

Vaccines have been shown to be an effective method for combating various infectious diseases. They provide a strong and direct defense against these illnesses and the deaths they can cause. However, millions of people in poor and developing countries still do not have access to vaccination due to high costs and storage challenges. Approximately 20% of infants are unvaccinated, leading to nearly 2 million preventable deaths each year, primarily in remote and underserved areas. [1]

Immunization has decisively reduced the spread of numerous infectious diseases, including tetanus, polio, and hepatitis. However, for certain diseases, effective immunization options remain unavailable, unreliable or expensive. [2]

While DNA vaccines have emerged as an alternative, they can lead to adverse immune reactions and often require refrigeration, complicating their storage and transportation. Oral vaccines represent a more cost-effective and accessible solution for the population in low-income areas. These vaccines are typically formulated from plants that express antigens, necessitating a foundation understanding of agriculture and plant cultivation. Furthermore, edible vaccines eliminate complex purification and downstream processes, significantly lowering production costs when compared to conventional vaccines. [3,4]

Edible vaccines are explicitly produced from transgenic plants and animals engineered to trigger an immune response in the body. Essentially, they are powerful medical therapies derived from plants or animals. This highlights the crucial importance of plant-based vaccines and the need for continued research and development in the promising field of edible vaccines. [5]

History of edible vaccines

In 1998, researchers supported by the National Institute of Allergy and Infectious Diseases (NIAID) achieved a groundbreaking milestone by proving that an edible vaccine can safely generate a powerful immune response in humans. [6]

These researchers emphasized that vaccines possess that exceptional potential to dramatically reduce the prevalence of diseases like hepatitis and diarrheal, particularly in developing countries where the challenges of storing and administering vaccines are significant, according to the then-director of NIAID. [7]

A crucial breakthrough occurred when researchers successfully expressed a surface antigen from hepatitis B and heat-labile toxin B antigens in potato plants. This represents a significant leap forward in the evolution of edible vaccine research, positioning it as a viable solution for global health challenges. [8]

Principle Of Edible Vaccines

Edible vaccines are transforming immunization by inserting specific genes into plants, which then produce the relevant proteins.[9] These transgenic plants undergo a process known as transformation. Edible vaccines consist of antigen proteins, free from harmful genes, making them safe even for immunocompromised individuals. [10]

Unlike conventional subunit vaccines, which are costly, complex, and often yield weak immune response, edible vaccines improve patient compliance- especially among children -and require no trained medical personnel for administration, as they are taken orally. [11]

Their efficient and scalable manufacturing process enhances accessibility.

Researchers have developed edible vaccines for various diseases, including cholera, measles, hepatitis B, C, and E. They can also combat rarer illnesses such as hookworm and dengue fever, especially when combined with other immunization strategies. Key crops like tomatoes, rice, bananas, and lettuce are used for production. [12]

When ingested, edible vaccines stimulate both mucosal and systemic immunity, providing essential protection against pathogens like Mycobacterium tuberculosis and those causing Diarrheal diseases.

Diarrheal pathogens account for about three million infant deaths annually, primarily in developing countries. Edible vaccines offer a vital solution to this urgent health crisis. [13]

Methods of Preparation of Edible Vaccines

Developing edible vaccines combines biotechnology, molecular genetics, and immunology to express proteins that provoke immune reactions in edible plant tissues. The process includes several steps:

1. Gene Selection and Isolation - The preparation of edible vaccines begins with the identification and isolation of the desired antigenic gene from a pathogenic organism responsible for a specific disease. This gene, once identified, is amplified and purified using molecular cloning techniques. The isolated sequence is selected based on its proven immunogenic potential and ability to elicit a protective immune response.[14]

2. Vector Construction - The selected antigenic gene is inserted into a suitable plant expression vector containing regulatory sequences such as promoters, enhancers, and terminators that ensure stable and efficient expression within plant cells. These vectors are designed to facilitate integration of the gene into the plant genome while maintaining optimal transcriptional control.[15,16]

3. Gene Transfer (Plant Transformation) - The recombinant vector is then introduced into the plant genome through transformation techniques. Among the various available methods, Agrobacterium tumefaciens-mediated transformation is most frequently employed due to its efficiency and stability. [17] In cases where this method is unsuitable, biolistic transformation (gene gun) or electroporation is utilized. These methods enable the precise delivery of foreign DNA into plant tissues or protoplasts, allowing the stable integration of the antigenic gene. [18]

4. Tissue Culture and Plant Regeneration - Once transformation is accomplished, tissue culture techniques are applied to regenerate complete plants from the genetically modified cells. The transformed cells are cultured on a nutrient medium supplemented with appropriate growth hormones under sterile and controlled environmental conditions. [19]

During regeneration, the integrated gene is expressed within the edible portions of the plant—such as leaves, fruits, tubers, or seeds—depending on the chosen host species. [20]

5. Screening and Molecular Confirmation - The regenerated plants are screened and characterized to confirm successful transformation and antigen expression. Molecular tools such as polymerase chain reaction (PCR), Southern blotting, and enzyme-linked immunosorbent assay (ELISA) are employed to verify gene insertion, transcriptional activity, and protein production. Transgenic lines showing stable inheritance and high antigen yield are selected for further propagation. [21]

6. Large-Scale Cultivation - Following successful screening, the selected transgenic plants are cultivated on a large scale under greenhouse or confined field conditions compliant with biosafety regulations. Proper containment practices are maintained to prevent unintended gene flow into the environment. Large-scale cultivation allows the mass production of plant material containing the vaccine antigen. [22]

7. Harvesting and Post-Harvest Processing - When the plants reach maturity, the antigen-containing tissues are harvested at the optimal growth stage. The harvested material is subjected to processing and stabilization techniques such as freeze-drying, lyophilization, or encapsulation to preserve the antigen's structural integrity and immunogenic activity. These steps ensure that the antigen remains stable during storage and transportation. [23]

8. Formulation and Delivery - After stabilization, the plant material is formulated into an edible dosage form suitable for human or veterinary consumption. [24]

Depending on the crop type and application, the vaccine may be administered directly as fresh produce or in processed forms such as capsules, dried powders, or tablets. This approach eliminates the need for injections and cold-chain systems. [25]

9. Quality Control and Regulatory Evaluation -

Before the vaccine can be approved for practical use, it undergoes rigorous quality control testing and regulatory evaluation. These assessments ensure that the vaccine is safe, effective, and consistent across production batches. Parameters such as antigen dose, immunogenic potency, and potential allergenicity are thoroughly examined in accordance with international biosafety standards. [26]

Through these systematically organized steps, edible vaccines are produced as stable, cost-effective, and scalable immunization agents. The integration of molecular biology with plant biotechnology allows for the development of oral, needle-free vaccines that can be stored and distributed easily, thereby improving vaccine accessibility in both human and veterinary medicine.

Immunological Mechanism of Edible Vaccines

The immunological mechanism of edible vaccines is based on the activation of both mucosal and systemic immune responses following the oral administration of antigen-expressing plant tissues. When an edible vaccine is consumed, the antigenic proteins produced within the plant cells are released in the gastrointestinal tract. These antigens are protected from immediate degradation by plant cell walls, allowing them to reach the small intestine in a partially intact form. Within the intestine, the antigens are recognized and captured by specialized cells of the mucosal immune system, particularly the microfold (M) cells located in the epithelial lining of Peyer's patches. [27,28]

Through these M cells, the antigens are transported across the intestinal epithelium and delivered to the underlying mucosa-associated lymphoid tissue (MALT). Once inside the MALT, the antigens are processed and presented by antigen-presenting cells (APCs), such as dendritic cells and macrophages. These APCs internalize the antigen, degrade it into peptide fragments, and present it on their surface via major histocompatibility complex (MHC) molecules. This antigen–MHC complex is then recognized by T-helper (CD4+) lymphocytes, leading to their activation. The activated T-helper cells, in turn, stimulate B lymphocytes to differentiate into plasma cells that secrete antigen-specific antibodies. [29]

The most critical outcome of this interaction is the production of secretory immunoglobulin A (IgA) on mucosal surfaces. Secretory IgA plays a key role in neutralizing pathogens at their entry points, preventing colonization and infection of mucosal tissues such as the respiratory and gastrointestinal tracts. Along with mucosal immunity, edible vaccines also induce systemic immune responses,

including the generation of immunoglobulin G (IgG) antibodies in the bloodstream. These IgG antibodies circulate throughout the body and provide long-term protective immunity against the corresponding pathogen. [30,31]

In addition to humoral immunity, cell-mediated immune responses are also activated by edible vaccines. Antigen presentation by dendritic cells and macrophages promotes the activation of cytotoxic T lymphocytes (CD8+ T cells), which recognize and destroy infected host cells expressing the antigen. This dual activation of both humoral and cellular arms of the immune system results in comprehensive and durable immune protection. [32]

Furthermore, edible vaccines have been found to stimulate tolerance modulation mechanisms, which prevent overactivation of the immune system. [33]

The balance between immune activation and tolerance induction depends on factors such as the dose of antigen, frequency of exposure, and the immunological environment of the gut. Proper formulation and dosage optimization can therefore ensure effective immunogenicity without inducing oral tolerance. [34]

The overall immunological mechanism of edible vaccines thus mimics the natural route of pathogen entry while providing antigen exposure in a safe, non-pathogenic context. By triggering mucosal, systemic, and cell-mediated immunity simultaneously, edible vaccines offer a multifaceted defense strategy against infectious diseases. This ability to elicit both local and systemic responses through an oral, needle-free approach highlights their potential as a next-generation platform for global immunization, particularly in regions where conventional vaccines face logistical and economic challenges. [35]

Table.1 METHOD OF PREPARATION -EDIBLEVACCINE

S.no	Title	Type of plant	Method of preparation	Year
1	Fruit based banana vaccine (hepatitis B)	Banana	Primary prepared using recombinant dna technology, insert the HBsAg gene isolate the gene into plant vector then then it develop whole plant using molecular techniques finally when the person is consumed orally, it triggers the immune response	2012
2	Cereal based rice vaccine (rota virus)	Rice	Primary prepared using recombinant dna technology ,insert the CT-B[cholera toxin-b sub unit] isolate the gene into plant vector then it develop the whole plant using molecular techniques finally when the person is consumed orally ,it triggers the immune response	2002
3	Vegetable based potato vaccine	Potato	Primary prepared using recombinant dna technology ,insert the LT-B[heat-labile toxin]. isolate the gene into plant vector then it develop the whole plant using molecular techniques finally when the person is consumed orally ,it triggers the immune response	Still experiment is going -potato
4	Leafy based lettuce vaccine (measles)	Lettuce	Primary prepared using recombinant dna technology ,insert the measles virus hemagglutitin. isolate the gene into plant vector then it develop the whole plant using molecular techniques finally when the person is consumed orally ,it triggers the immune response	2008
5	Legume based chickpea vaccine(cholera virus)	Legume based vaccine-chickpea	First select the gene(CT-B).insert the binary vector like pCAMBIA and inject the dicot legumes preferly suitable for chickpea and cultivate them .when it is completed regenerate whole plants and transfer them to soil confirm with the seeds or leaves or transcription. These antigen can stored in seeds and the people can consume directly (after drying,milling the flour) or encapsulated into tablets.	2009

Evaluation of Edible Vaccine [36]

The evaluation of plant-based edible vaccines has been conducted through a rigorous sequence of preclinical and clinical investigations to ensure safety, immunogenicity, and product consistency.[36] Edible vaccines, in which antigens are expressed in edible plant tissues and delivered orally, have been proposed as an innovative means of inducing both mucosal and systemic immunity without the need for parenteral administration.[37] These vaccines are regulated as biological products rather than as foods, and early Phase I trials involving potato- and corn-based enterotoxigenic E. coli (ETEC) [38] and hepatitis B virus (HBV) candidates have demonstrated acceptable safety and measurable immune responses in human volunteers.[39] The development and assessment process proceeds from preclinical animal studies to phased clinical trials, with emphasis placed on antigen expression, immune activation, and biosafety.[40]

Preclinical Evaluation

During preclinical development, animal models such as mice, rabbits, and pigs have been employed to assess immunogenicity, antigen stability, and potential toxicity.[36] In these studies, transgenic plant materials or their extracts are administered orally, and immune responses are quantified through measurements of antigen-specific serum IgG and mucosal IgA. [37] Protection is then evaluated by challenge with the relevant pathogen or toxin.[41] For instance, oral administration of MucoRice-CTB, a rice-based cholera vaccine expressing the cholera toxin B subunit, was shown to elicit strong CTB-specific IgA and IgG antibodies in mice and to confer protection against cholera toxin challenge.[36] Similarly, the TOMAVAC tomato vaccine expressing the SARS-CoV-2 S1 antigen induced a significant rise—approximately sixteen-fold—in neutralizing anti-RBD IgG titers in serum, together with marked intestinal IgA production.[42]

Verification of stable transgene integration and antigen expression is routinely conducted using molecular and biochemical assays.[40] PCR and Southern blot analyses are used to confirm gene insertion and stability, while antigen yields in plant tissues are quantified by ELISA, Western blotting, and mass spectrometry.[43] In the case of MucoRice-CTB, SDS-PAGE densitometry revealed an antigen concentration of about 4.9 μg CTB per milligram of dry seed.[41] These evaluations have also examined the role of plant cell walls and tissue matrices in protecting the antigen through digestion, thereby maintaining bioavailability in the intestinal tract.[44]

Toxicity and allergenicity testing form essential parts of preclinical assessment.[36] Animals are monitored for changes in weight, behavior, organ histopathology, and blood parameters to identify any adverse effects.[36] Because edible vaccines are consumed in relatively high doses, the potential induction of oral tolerance is evaluated, and formulation strategies such as the inclusion of adjuvants or bioencapsulation are tested to ensure the induction of active immunity rather than tolerance.[44] Allergic potential is also assessed by detecting IgE cross-reactivity with plant proteins or by observing allergic manifestations.[45]

Clinical Evaluation

Human clinical evaluation of edible vaccines follows the established Phase I–III vaccine development pathway but is adapted for oral delivery systems.[36]

In Phase I trials, small groups of healthy volunteers are enrolled to determine safety, tolerability, and preliminary immunogenicity.[36] A representative example is provided by the Phase I trial of MucoRice-CTB, in which healthy adults received 6 g of vaccine powder either as a single or repeated dose in a randomized, double-blind, placebo-controlled study.[36] The formulation was found to be safe, well tolerated, and capable of inducing both serum IgG and salivary IgA specific for CTB.[36] Participants were monitored for reactogenicity, gastrointestinal symptoms, and other adverse events, none of which were severe.[36]

Phase II trials are then conducted to optimize dose and schedule and to expand the assessment of immune responses.[36] These studies often measure geometric mean titers of serum IgG and IgA and, where ethical, may include challenge components to assess protective efficacy.[45] Given the oral route of administration, mucosal immune endpoints such as fecal or nasal IgA concentrations are emphasized.[37]

In Phase III trials, larger cohorts are studied to determine vaccine efficacy against natural infection or disease.[36] Endpoints typically include reductions in infection incidence, seroconversion rates, and durability of immune responses, with continued monitoring for gastrointestinal or allergic reactions related to the plant matrix.[36]

The immune responses elicited by edible vaccines are evaluated through a variety of laboratory assays.[41] ELISA is employed to quantify antigen-specific antibodies in serum, saliva, or stool, while neutralization assays—such as virus neutralization or surrogate virus neutralization tests (sVNT)—are used to determine antibody functionality.[38] In the TOMAVAC study, SARS-CoV-2 RBD-

specific IgG was detected by ELISA and shown to possess neutralizing activity in sVNT assays.[42] Similarly, antibodies from MucoRice-CTB recipients inhibited CTB binding to GM1 ganglioside receptors, confirming functional activity.[41]Additional analyses such as ELISpot and intracellular cytokine staining may be used to evaluate T-cell responses when systemic cellular immunity is relevant.[36]

Evaluation Parameters for Edible Vaccines [46]

Parameter	Description
Immunogenicity	Ability to induce a protective immune response.
Stability	Retention of antigen structure during storage and digestion.
Dosage Control	Standardization of antigen concentration.
Safety	Absence of allergenic or toxic effects.
Public acceptance	Social and ethical considerations of GMO vaccines.

Regulatory and Ethical Considerations

The regulatory framework governing edible vaccines aligns with existing biologics and vaccine guidelines. [47] These products are classified as vaccines rather than food products and must comply with national and international requirements (e.g., FDA, EMA, and WHO guidelines).[47] Evaluation focuses on product characteristics rather than the method of plant production.[36]Stringent quality controls are imposed to ensure stable transgene expression, batch consistency, and absence of contaminants.[35] Because production often involves genetically modified crops, biosafety regulations and environmental containment measures are enforced, requiring authorization from relevant agricultural and biosafety agencies.[47] Ethical oversight of clinical trials includes informed consent procedures, clear disclosure regarding the genetically modified nature of the product, and careful monitoring for allergenicity or unexpected adverse events.[36]

Case Examples

Two representative edible vaccines have been studied extensively.[36] MucoRice-CTB, produced in a hydroponic rice cultivation system, was shown to contain approximately 5 μg of CTB per milligram of seed and to induce strong systemic and mucosal immunity in both animal models and humans without significant adverse effects.[37] The TOMAVAC vaccine, produced in transgenic tomatoes expressing the SARS-CoV-2 spike S1 subunit, demonstrated robust humoral and mucosal responses in mice and promising immunogenicity in an initial human proof-of-concept study.[37] Earlier candidates—such as potato or maize vaccines expressing Norwalk virus or ETEC antigens—provided additional proof-of-concept for mucosal immunization through plant matrices.[37]

Overall, the evaluation of plant-based edible vaccines has demonstrated that these platforms can elicit both mucosal and systemic immune responses while maintaining favorable safety profiles.[37] Continued optimization of antigen expression, formulation, and clinical assessment is expected to advance these vaccines toward practical application in public health.[40]

Future Perspectives

The development of plant-based edible vaccines is being increasingly viewed as a transformative approach for global immunization strategies, particularly in resource-limited settings where cold chain dependence and injection-based delivery pose significant challenges.[36] Despite encouraging preclinical and early clinical outcomes, several technical, regulatory, and logistical issues remain to be addressed before widespread implementation can be achieved.[36]

One of the major scientific challenges lies in achieving consistent and sufficiently high antigen expression in plant tissues.[40] Variation in transgene expression caused by genomic position effects, environmental conditions, or plant developmental stage can lead to batch-to-batch variability in antigen yield.[40] Ongoing research is focusing on optimizing plant expression systems through the use of stronger promoters, codon optimization, and chloroplast transformation, which allows high-level expression and reduces the risk of transgene escape through pollen.[40] Standardized purification and quantification methods are also being developed to ensure consistent antigen content across production batches.[36]

Another critical issue concerns oral bioavailability and immune modulation.[36] Because orally administered antigens are exposed to digestive enzymes and acidic conditions, antigen degradation may reduce immunogenicity.[36] Strategies such as bioencapsulation within plant cell walls, lyophilization, or formulation with mucosal adjuvants are being explored to enhance antigen stability and delivery to gut-associated lymphoid tissues.[37] Additionally, understanding the balance between mucosal tolerance and active immune stimulation is essential, as excessive oral dosing could induce immune unresponsiveness.[37]

From a regulatory and manufacturing perspective, harmonized international guidelines will be necessary to facilitate approval and commercialization.[47] Current regulations for biologics provide a foundation, but additional provisions related to the use of transgenic plants, environmental biosafety, and quality control are required.[40]

Controlled cultivation environments—such as hydroponic or plant factory systems—are being promoted to minimize environmental risks and improve production consistency.[41] Advances in containment technology and traceability will further strengthen regulatory confidence and public acceptance.[47]

Public perception and ethical considerations also play a decisive role.[45] Because edible vaccines are derived from genetically modified plants, societal acceptance depends on transparent communication of safety data, ethical trial conduct, and education about the scientific principles underlying the technology. [36] Engagement with communities, healthcare providers, and policymakers will be essential to foster trust and acceptance.[45]

Looking forward, the integration of edible vaccine platforms with emerging technologies such as mRNA-based antigens, nanoparticle carriers, and plant-virus expression systems may further enhance their immunogenicity and versatility.[40] Co-expression of multiple antigens could enable multivalent vaccines against several pathogens within a single plant product.[40] Moreover, personalized or region-specific edible vaccines may be developed to target local disease burdens, offering tailored immunization strategies.[36]

Edible vaccines are a developing innovation that combines biotechnology and immunology for better disease prevention. They offer an efficient, affordable, and patient-friendly way to get vaccinated. While progress has been made, optimizing antigen expression, ensuring safety, and obtaining regulatory clearance are essential next steps. Ongoing research and public education will be vital for their successful use.

In summary, the future of plant-based edible vaccines depends on continued interdisciplinary progress in plant biotechnology, immunology, and regulatory science.[47] With improvements in antigen expression, formulation, and public communication, edible vaccines have the potential to become safe, stable, and cost-effective tools for disease prevention—particularly valuable for low-resource regions and for rapid deployment in pandemic situations.[40] The promising outcomes from MucoRice-CTB and TOMAVAC studies indicate that the concept has moved beyond proof-of-principle and is advancing steadily toward real-world application.[41]

Table 2: Standardized evaluation checklist [36]

Section	Item	Minimum reporting requirement
Molecular	Antigen sequence & construct	Full sequence, promoter, fusion/adjuvant (e.g., CTB), Expression cassette map
Molecular	Expression quantifies	µg antigen / g fresh weight (ELISA) with LOD/LOQ & Standard curve
Stability	Storage stability	Antigen remaining (%) at 0,1,3,6 months at ambient and 4°C
Stability	Simulated GI digestion	% intact antigen after SGF + SIF assay; method details
Immunogenicity	Mucosal endpoints	sIgA absolute titers (ELISA), sampling method & units
Immunogenicity	Systemic endpoints	Serum IgG titer; neutralization assay (if available)
Immunogenicity	Cellular immunity	ELISpot/ICS details (antigen dose, readout)
Dosing	Dose per administration	µg antigen per serving; mass/volume per dose
Safety	Toxicology	Clinical chemistry, histopathology, animal welfare notes
Environmental	Containment	Field trial containment, pollen control, chloroplast vs nuclear insertion
Regulatory	Pathway	List national regulators consulted and required approvals

Table 3. Clinical Trials on Edible Vaccines (26)

Disease targeted	Plant uesd	Antigen/protein expressed	Trail findings and status
Hepatitis B	Potato (transgenic)	Hepatitis B surface antigen (HBsAg)	The first successful human clinical trial was conducted in 2005. - Volunteers consumed uncooked, transgenic potatoes. - A significant number of volunteers (62.5%) who consumed three doses showed an increase in serum anti-HBsAg titers. - This demonstrated that a plant-derived oral vaccine could safely elicit an immune response.
Cholera	Rice(transgenic)	Cholera toxin B subunit (CTB)	A Phase I human trial of a powdered rice-based vaccine (MucoRice-CTB) was conducted. The vaccine was found to be safe with no significant side effects. - It successfully elicited a good immune response, with participants developing CTB-specific IgA and IgG antibodies. The immune response was dose-dependent, with higher doses leading to a stronger response.
Norwalk virus	Potato (transgenic)	Norwalk virus capsid protein	One of the earliest human trials (Phase I) of an edible vaccine was conducted in the late 1990s. Volunteers who consumed raw, transgenic potatoes showed an immune response. While 95% of volunteers showed some form of immune response, the increase in antibodies was often moderate. This trial was a crucial proof-of-concept for edible vaccines in humans.
Enterotoxigenic E.coli(ETEC)	Potat (transgenic)	Heat-labile enterotoxin (LT)	Human trials demonstrated that consuming transgenic potatoes expressing the LT protein could elicit both systemic (serum) and mucosal (intestinal) immune responses. The

			vaccine was well-tolerated, and volunteers showed strong immune responses after a few doses. This research was important for demonstrating the potential of edible vaccines against pathogens causing "traveler's diarrhea."

While there have been many promising pre-clinical studies and early-phase clinical trials, no edible vaccine has been approved by a major regulatory body like the FDA for widespread human use. The technology faces significant challenges, including ensuring a consistent and stable antigen dose in the plant, the potential for degradation of the antigen by digestive enzymes, and navigating regulatory hurdles for genetically modified crops. However, the potential for a cost-effective and easily accessible vaccination method continues to drive research in this field.

CONCLUSION:

Edible vaccines offer a novel and sustainable approach to immunization by combining biotechnology with agriculture to produce antigenic proteins in edible plants. They present significant advantages such as needle-free administration, improved patient compliance, cost-effectiveness, and elimination of cold-chain requirements. These features make edible vaccines especially suitable for large-scale immunization programs in developing and resource-limited regions. Moreover, their ability to stimulate mucosal immunity enhances protection against enteric pathogens. However, challenges related to dosage control, antigen stability, regulatory approval, and public acceptance of genetically modified crops must be addressed. With continued research, technological advancements, and supportive regulatory policies, edible vaccines have the potential to complement conventional vaccines and play a vital role in future global public health initiatives.

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